IMPROVING COORDINATED TRAFFIC SIGNAL TIMING THROUGH CONNECTED VEHICLE TECHNOLOGY

by

Yuan Hu

B.S. Engineering, North China University of Water Resources and Electric Power, 2012

M.S. Civil Engineering, University of Pittsburgh, 2014

Submitted to the Graduate Faculty of

The Swanson School of Engineering in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy in Civil Engineering

University of Pittsburgh

2016

UNIVERSITY OF PITTSBURGH

SWANSON SCHOOL OF ENGINEERING

This dissertation was presented

by

Yuan Hu

It was defended on

March 30th, 2016

and approved by

Leonard Casson, PhD, PE, Associate Professor, Department of Civil & Environmental Engineering

John Brigham, PhD, Associate Professor, Department of Civil and Environmental Engineering

Vikas Khanna, PhD, Assistant Professor, Department of Civil and Environmental Engineering

Mark Szewcow, PE, Adjunct Lecturer, Department of Civil and Environmental Engineering

Ervin Sejdic, PhD, Assistant Professor, Department of Electrical and Computer Engineering

Dissertation Director: Mark Magalotti, PhD, PE, Senior Lecturer, Department of Civil and Environmental Engineering

IMPROVING COORDINATED TRAFFIC SIGNAL TIMING THROUGH CONNECTED VEHICLE TECHNOLOGY

Yuan Hu, Ph.D.

University of Pittsburgh, 2016

For coordinated traffic control systems of traffic signals, timing offset is an important parameter that should account for the effect of queued vehicles at signals, travel speeds between intersections and the roadway geographic characteristics. In order to improve coordinated signal timing in the short term, this dissertation research developed an approach to optimize timing offset based on queue length information that will soon be available from connected vehicles (CVs) in the near future. The benefits of this approach were measured in an urban street corridor network and a suburban highway corridor network using the simulation program VISSIM.

The simulation results shows that using the queue measurements in signal retiming provided a better optimized signal coordination during the peak hours. Up to 21.6% less delay and 13.9% less stops when compared to the current signal retiming approach. Based on multiple runs of simulation under different connected vehicle market penetration rates, at least 60% penetration rate was required for this approach.

TABLE OF CONTENTS

1.0 INTRODUCTION 1

1.1 BACKGROUND 1

1.1.1 Traffic signal timing coordination 2

1.1.2 Connected Vehicle (CV) technology 2

1.2 HYPOTHESIS 3

1.3 OBJECTIVES 4

1.4 METHODOLOGY 5

2.0 LITERATURE REVIEW 7

2.1 INTRODUCTION 7

2.2 VEHICLE-TO-VEHICLE (V2V) DEPLOYMENT 8

2.2.1 FHWA 8

2.2.2 USDOT 8

2.3 VEHICLE-TO-INFRASTRUCTURE (V2I) DEPLOYMENT 9

2.3.1 FHWA 9

2.3.2 State DOTs 9

2.3.3 Connected vehicle traffic operation research 10

2.4 SUMMARY 13

3.0 APPROACH FOR TESTING THE HYPOTHESIS 15

3.1 INTRODUCTION 15

3.2 THEORY AND EQUATION.. 16

3.2.1 Queue length 16

3.2.2 Timing offset 16

3.3 DEVELOPMENT OF METHODOLOGY 18

3.4 TESTING THE HYPOTHESIS 19

3.4.1 Test sites... 19

3.4.1.1 U.S. Route 22 19

3.4.1.2 Baum-Centre corridor in Pittsburgh, PA 21

3.4.2 Data collection.. 21

3.4.2.1 Traffic volumes.. 21

3.4.2.2 Timing plans 22

3.4.2.3 Queue length... 22

3.4.3 Model development.. 23

3.4.3.1 Scenario I: Coordinated TOD timings traffic operation................. 24

3.4.3.2 Scenario II: Improved coordinated traffic operation...................... 24

3.4.3.3 Scenario III: Improved traffic operation with alternative offsets.. 25

3.5 DETERMINING THE REQUIRED CV PENETRATION RATE............... 25

3.6 SUMMARY 26

4.0 TEST RESULTS 27

4.1 INTRODUCTION 27

4.2 SIMULATION RESULTS.. 28

4.2.1 William Penn Highway network 28

4.2.2 Baum-Centre corridor Network 33

4.3 ANALYSIS OF RESULTS 40

4.3.1 Efficiency in Peak Hours 41

4.3.1.1 Network performance 41

4.3.1.2 LOS of intersections 46

4.3.1.3 Travel time 49

4.3.2 Efficiency in Off-peak Hours 53

4.3.2.1 Network performance 55

4.3.2.2 LOS of intersections 58

4.3.2.3 Travel time 59

4.4 REQUIRED CV MARKET PENETRATION RATE 61

5.0 SUMMARY AND CONCLUSIONS 65

5.1 SUMMARY OF RESULTS 65

5.1.1 Network performance 65

5.1.2 LOS of Intersections 66

5.1.3 Travel Time 66

5.2 CONCLUSIONS 67

5.3 RECOMMENDATIONS FOR FUTURE RESEARCH 68

APPENDIX A 69

BIBLIOGRAPHY 74

LIST OF TABLES

Table 1. MAPE in queue length estimation developed using probe trajectory data 13

Table 2. The summary table of the two test corridor networks 19

Table 3. The numbered roadway intersections in the William Penn Hwy network 28

Table 4. William Penn Hwy network performance MOEs in Scenario 1 29

Table 5. LOSs of the intersections along William Penn Hwy in Scenario 1 30

Table 6. Average travel time of vehicles in the William Penn Hwy network in Scenario 1 30

Table 7. William Penn Hwy network performance MOEs in Scenario 2 31

Table 8. LOSs of the intersections along William Penn Hwy in Scenario 2 31

Table 9. Average travel time of vehicles in the William Penn Hwy network in Scenario 2 32

Table 10. William Penn Hwy network performance MOEs Scenario 3 32

Table 11. LOSs of the intersections along William Penn Hwy in Scenario 3 33

Table 12. Average travel time of vehicles in the William Penn Hwy network in Scenario 1 33

Table 13. The numbered roadway intersections in the Baum-Centre corridor network 34

Table 14. Baum-Centre corridor network performance in Scenario 1 34

Table 15. LOSs of the intersections along Baum-Centre Corridor in Scenario 1 35

Table 16. Average travel time of vehicles in the Baum-Centre Corridor network in Scenario 1. 36

Table 17. Baum-Centre Corridor network performance in Scenario 2 37

Table 18. LOSs of the intersections along Baum-Centre Corridor in Scenario 2 37

Table 19. Average travel time of vehicles in the Baum-Centre Corridor network in Scenario 2. 38

Table 20. Baum-Centre Corridor network performance in Scenario 3 39

Table 21. LOSs of the intersections along Baum-Centre Corridor in Scenario 3 39

Table 22. Average travel time of vehicles in the Baum-Centre Corridor network in Scenario 3. 40

Table 23. William Penn Highway network performance under different CV market penetration rates 62

Table 24. Baum-Centre corridor network performance under different CV market penetration rates 63

Table 25. Average queue length and platoon speed for intersections along William Penn Hwy. 70

Table 26. Average queue length and platoon speed for intersections along Baum-Centre corridor 71

Table 27. Optimal timing offsets for intersections along William Penn Hwy 72

Table 28. Optimal timing offsets for intersections along Baum-Centre corridor 73

LIST OF FIGURES

Figure 1. The illustration of testing methodology used in the research 18

Figure 2. The study segment of U.S. Route 22 in Murrysville, Pennsylvania (part a) 20

Figure 3. The study segment of U.S. Route 22 in Murrysville, Pennsylvania (part b) 20

Figure 4. A segment of Baum-Centre corridor in the city of Pittsburgh, Pennsylvania 21

Figure 5. The flow diagram of development of the traffic scenarios 24

Figure 6. Average delay per vehicle in the William Penn Highway network during AM peak ... 42

Figure 7. Average delay per vehicle in the William Penn Highway network during PM peak 42

Figure 8. Average delay per vehicle in the Baum-Centre Corridor network during AM peak 43

Figure 9. Average delay per vehicle in the Baum-Centre Corridor network during PM peak 43

Figure 10. Average number of stops in the William Penn Highway network during AM peak .. 44

Figure 11. Average number of stops in the William Penn Highway network during PM peak ... 45

Figure 12. Average number of stops in the Baum-Centre Corridor network during AM peak 46

Figure 13. Average number of stops in the Baum-Centre Corridor network during PM peak 46

Figure 14. LOS of intersections along William Penn Highway in the AM peak 47

Figure 15. LOS of intersections along William Penn Highway in the PM peak 47

Figure 16. LOS of intersections along Baum-Centre Corridor in the AM peak 48

Figure 17. LOS of intersections along Baum-Centre Corridor in the PM peak 49

Figure 18. Average travel time for the two identified routes along William Penn Hwy in AM peak 50

Figure 19. Average travel time for the two identified routes along William Penn Highway in PM peak 50

Figure 20. Average travel time for the four identified routes along Baum-Centre Corridor in AM peak 52

Figure 21. Average travel time for the four identified routes along Baum-Centre Corridor in PM peak 53

Figure 22. Time-space diagram of int. of William Penn Hwy & Branthoover Cutoff in the AM peak hour 54

Figure 23. Time-space diagram of int. of William Penn Hwy & Branthoover Cutoff in the MD hour 55

Figure 24. Average delay per vehicle in the William Penn Highway network during MD hour . 56

Figure 25. Average delay per vehicle in the Baum-Centre Corridor network during MD hour... 56

Figure 26. Average number of stops in the William Penn Highway network during MD hour... 57

Figure 27. Average number of stops in the Baum-Centre Corridor network during MD hour 58

Figure 28. LOS of intersections along William Penn Highway in the MD hour........ 59

Figure 29. LOS of intersections along Baum-Centre Corridor in the MD hour 59

Figure 30. Average travel time for the two identified routes along William Penn Hwy in MD hour 60

Figure 31. Average travel time for the two identified routes along Baum-Centre Corridor in MD hour 60

1.0 INTRODUCTION

Traffic engineers have always been concerned with how to manage roadway network capacity more efficiently in order to reduce traffic congestion. With the development of connected vehicle (CV) technology, data from CVs will soon be available to improve the efficiency of traffic signal systems as well as for many other applications. This dissertation research developed an approach to utilize data obtained from CVs to improve signal timing coordination of Time-of-Day (TOD) traffic control strategies.

The following section of the chapter introduces the research background, hypothesis, objectives and methodology.

1.1 BACKGROUND

Although various traffic signal timing strategies have been developed since the late 1970s, a large number of agencies still generally use hourly vehicle turning movement counts, collected on a sampling basis, to set Time-of-Day (TOD) timing plans for signalized intersections. However, this data may not necessarily reflect the true state of the traffic network at any given time because it is difficult to measure variability in vehicle volumes using this method.

A new emerging technology, named Connected Vehicle (CV) technology, may change the situation because it can be used to provide agencies with massive traffic information that gives a true picture of roadway traffic. The researchers developed a method to improve traffic management based on the CV technology.

1.1.1 Traffic signal timing coordination

Traffic signal timing coordination is the primary way for managing traffic demand along arterial streets and in grid networks. This traffic signal control strategy coordinates green time of signals to serve traffic flows. In a coordinated traffic signal system, all signals have the same cycle length and vehicles often arrive at the downstream intersection in platoons. Timing offsets between signals help these vehicles move smoothly through the coordinated signals.

The determination of timing offset is mainly relative to distance between intersections and vehicle speed. Because in practice there may be a queue standing at the downstream intersection when vehicles from the upstream intersection arrival, offset should also be adjusted to allow for queue clearance. But it is difficult to know the exact queue size at each signal. Therefore, in most cases, timing offset is set based on algorithms of traffic simulation programs, rather than actual queue size. It is possible that the offset determined by programs is not same as the suitable offset in the real situation, and there may be the potential for improvement of traffic signal coordination if true queue size could be captured.

1.1.2 Connected Vehicle (CV) technology

Over the past few years the rapid development of computer and telecommunication technologies has bred Connected Vehicles (CVs), a new type of vehicles equipped with the connectivity of devices. With the introduction of CVs, Vehicular Ad-Hoc Networks (VANETs) will form to implement V2V (Vehicle to Vehicle) or V2I (Vehicle to Infrastructure) communications. These dedicated short-range communication technologies allow a vehicle to connect to its surroundings and exchange data with vehicles and infrastructures in both near and far environment. Basic operating information for individual vehicles such as vehicular location, speed and direction will be transmitted through V2V or V2I communications providing an efficient way for improved traffic data collection. This will provide more data on real time traffic conditions than fixed-point detectors, which can only provide count, speed and occupancy data, making possible better traffic management.

Presently the penetration ratio of equipped vehicles is extremely low in the nation. Only the State of California's policy allows connected vehicles running on a highway without special approvals for research purposes. Even if a mandatory rule was enacted for vehicle manufacturers to provide this technology, it may take several decades for connected vehicles to reach a market penetration rate of significance. However, the initial literature research has revealed [Feng et al., 2015] that the number of queued vehicles at intersections can be estimated accurately with a comparatively low penetration rate of connected vehicles.

1.2 HYPOTHESIS

The hypothesis is that basic vehicular information available from connected vehicles and transmitted through Vehicle to Infrastructure (V2I) communications could be used in the optimization of traffic signal systems. A corollary to this is to determine at what penetration rate of connected vehicles accurate average queue length data will be available to be of significance in determining optimal coordinated timing offsets.

On the basis of the hypothesis, the researchers proposed a method that utilizes data obtained from connected vehicles to improve coordinated traffic signal control operations along an arterial road. Improving coordination is an important research topic since it is a primary strategic approach to reducing vehicle travel times, stops and delay for a whole corridor or roadway network.

1.3 OBJECTIVES

The primary objective of the research was testing the proposed method for retiming traffic signal systems on corridors. Because the introduction of CVs will be staggered over time, the research also examined the minimum required market penetrate rate of CVs in the traffic stream for this approach.

Time of Day (TOD) timing plans is anticipated to be a common control strategy used for traffic signal systems in the United States for many years. Therefore, it is viable to incorporate sampling queue length information that becomes available as connected vehicles emerge into traffic signal retiming processes to improve TOD timing coordination. To sum up, the objectives of this research were to:

- Determine if using connected vehicle information improves existing TOD traffic signal coordinated control by determining offsets using this information;
- Determine the minimum required market penetration rate of connected vehicles for the proposed signal retiming application; and
- Explore how the use of CV information optimizes signal coordination for future signal retiming on corridors.

1.4 METHODOLOGY

The research focused on developing and evaluating the benefits of a method to use data from CVs for retiming TOD traffic signal control systems. Generally when retiming Time-of-Day (TOD) plans at an intersection, the following steps are recommended:

1) Perform a qualitative evaluation of the intersection performance every three years.
2) Collect updated traffic count data for selected peak hours
3) Run Syncrho or the other methods which optimizes timings and develops offsets.
4) Adjust the cycle length and splits to reflect demand on competing approaches.
5) Adjust the timing offset to reflect platoon arrival times.
6) Re-program signal control.
7) Repeat field observation to confirm improvements.

There is one thing different in the proposed method. The program Synchro was used to optimize timing plans for signals, but not to develop offsets. The researchers determined the offsets based on distance between signals, platoon speed and queuing information. Downstream queue lengths would be measured in the field by V2I infrastructure, but no such infrastructure exists today. In order to test the hypothesis, the program SimTraffic was be used to provide the simulated CV queue lengths and TOD optimized timings.

The testing of the hypothesis was accomplished based on the simulation results produced by the software VISSIM. VISSIM is a microscopic simulation model widely used to analyze performance of traffic facilities. The model development and simulation is quite complex requiring great data processing operations during the development phase. However, the complicated calibration process supports very high validity of the resulting model’s outputs. To ensure roadway data consistency, traffic models was carefully built in Synchro, and then imported to the program VISSIM.

Maximum queue length is used for a validation measure under VISSIM simulation models. But in this case, VISSIM was used to simulate traffic signal operation with projected timings and offsets and the corresponding queue lengths that are only available in the simulation environment. Although advanced detectors such as Bluetooth detectors could be used to collect queuing data in the field, the field data cannot be used for validation because it’s measured under current signal operations instead of the revised operations with the measured queue length. Hence, it’s not very feasible to validate the VISSIM simulation results in the field. Future research would be performed to validate the results once a significant number of CVs are present.

2.0 LITERATURE REVIEW

This chapter presents the literature review on the research topic. The purpose of this literature review is to determine whether information from any study or report would aid in developing the proposed methodology to use connected vehicle data to improve signal control strategies.

2.1 INTRODUCTION

The advent and development of connected vehicle (CV) technologies offer the potential for significant improvements in traffic mobility and safety. Theoretically, connected vehicles can provide more traffic information, such as vehicular location, speed and queue length, through Vehicle to Vehicle (V2V) or Vehicle to Infrastructure (V2I) communications, which could contribute to the achievement of better travel services and traffic facilities operations. The following exhibits valuable studies and practices on the applications using CV data conducted by United States national traffic agencies, State Departments of Transportations (DOTs), and research centers.

2.2 VEHICLE-TO-VEHICLE (V2V) DEPLOYMENT

2.2.1 FHWA

The Federal Highway Administration (FHWA) is currently performing a study [FHWA, 2015] that has a goal to identify State and local policy and planning actions that stimulate the development of markets for connected vehicle and automated vehicle system. This study is under the National Cooperative Highway Research Program (NCHRP) Project 20-102 that is examining a variety of CV issues.

2.2.2 USDOT

The United State Department of Transportation (USDOT) has explored the use of CV and V2V technologies to improve traffic safety since 2002. A queue warning application was developed [USDOT, 2015] to notify drivers that there is a queue ahead so that they can reduce speed in advance to avoid a sudden braking operation. Some tests were performed on test beds established under a safety pilot program to assess drivers' acceptance of the new connected vehicle technologies. Most feedback from the test drivers was positive. In 2011 the Data Capture and Management (DCM) program established and proved [Balke et al., 2014] that collecting real-time data relayed from connected vehicles is both possible and practical.

State departments of transportation (DOTs) are devoting research to V2V deployment. Louisiana DOT will conduct connected vehicle research [Louisiana Transportation Research Center, 2015] in operation and safety areas using a driving simulator. Texas DOT will investigate [Texas DOT, 2015] existing and emerging VANET (Vehicular Ad-hoc Network) technologies in connected vehicle environments.

2.3 VEHICLE-TO-INFRASTRUCTURE (V2I) DEPLOYMENT

2.3.1 FHWA

FHWA published [FHWA, 2015] V2I deployment guidance to assist traffic engineers and system owners/operators in planning for CV/V2I deployments. Although deployment of V2I technologies is not mandated, this guidance is a useful resource to help engineers who are beginning to think about the deployment of V2I systems. According to this guidance, FHWA strongly encourages agencies to consider V2I strategies in the early planning stage of traffic projects. Expenses associated with V2I applications, such as installation, operational and maintenance costs, are eligible for Federal-aid funding. Deployment of V2I services is covered under the Code of Federal Regulations (CFR) in the Intelligent Transportation Systems (ITS) section, and conforms to criteria of certain existing ITS. The ITS Evaluation Resource Guide is recommended to determine the effectiveness of V2I applications.

2.3.2 State DOTs

Many State Departments of Transportation (USDOTs) have been involved in researching connected vehicle technologies. Washington State DOT would like to identify [Washington DOT, 2015] a method to select appropriate applications used in connected vehicles from current market products and study data obtained from connected vehicles. Florida DOT is also interested [Florida DOT, 2015] in the utilization of the CV data. In addition, Florida DOT is refining

[Florida DOT, 2015] an existing algorithm and related software and hardware for traffic signal control optimization by testing control operations in a closed course environment.

California DOT developed and tested [Skabardonis, 2013] control strategies for queue spillback avoidance, congestion avoidance and dynamic lane grouping based on data collected from connected vehicles. In the estimation of queue length, researchers preferred a method that estimates the queue length based on the distance between connected vehicles and the intersection, assuming that the position of the vehicles in the queue is discrete and uniformly distributed and at least two connected vehicles exist in queue per lane. The simulation result shows that the estimated queue length is apparently shorter than the actual queue length because the last vehicle in queue, which is always unequipped with a connectivity device, could not be counted. It was concluded that estimation could be guaranteed when 80% of the vehicles are equipped using this method. It requires a higher penetration rate to obtain an accurate queue length for under saturated traffic conditions (traffic volume/capacity < 1) than oversaturated conditions (V/C ratio > 1).

2.3.3 Connected vehicle traffic operation research

The University of Virginia proposed [Lee et al., 2013] a real-time traffic control algorithm that employs the cumulative travel times at an interval collected from the connected vehicles. This algorithm can determine green time and phase sequence in favor of the highest cumulative travel time phase. Kalman filtering was utilized to estimate the cumulative travel times of vehicles unequipped with the connected vehicle devices under imperfect penetration rates. Researchers simulated a four-way intersection and measured the benefits of the algorithm under different traffic demand patterns and market penetration rates in VISSIM. The simulation results show that the algorithm improves mobility of the intersection when the connected vehicle market penetration rate exceeds 30%.

Researchers from the University of Arizona proposed [Feng et al., 2015] an adaptive signal algorithm that takes advantage of trajectory data from connected vehicles. The algorithm is to minimize vehicle delay or queue length by optimizing phase sequence and duration. In order to validate the algorithm, signal control strategies and traffic demand levels at a real-world four-way intersection were modeled in VISSIM under varying vehicle market penetration rates. For each approach, the road segment near the intersection was divided into three regions: queuing, slow-down and free-flow. Based on the location and speed of connected vehicles, the status of unequipped vehicles in these three regions was respectively estimated using different methods. The preferred method is to estimate the queue length based on the location and stopping time of the last connected vehicle in queue. If some unequipped vehicles join the queue after the last connected vehicle, queue propagation speed is assumed to remain the same as the previous arrival rate. The estimation of vehicles in the queuing region always had good performance, even at a penetration rate of 25%. With data on vehicle status in different regions, the researchers identified the improvement of the proposed algorithm compared to the actuated control when penetration rate is equal to or greater than 50%.

Swiss scientists have developed [Guler et al., 2014] an algorithm to minimize vehicle delay or number of stop by adjusting phase sequences. An intersection of two one-way streets was built in a simulation environment. Connected vehicle data: the time a car enters the intersection area and the relative position of a car that comes to a stop apart from the intersection, was used to estimate the time when cars arrive at the intersection and the time needed for discharging queued cars. It is assumed that only some of the vehicles are connected. The variable factors in the research are the penetration rate and the type of demand pattern. The results show that when the penetration rate rises from 0 to 60 percent, the average delay is decreased in demand scenarios using the algorithm.

A research study published in the *Transportation Research Record* uses [Li et al., 2013] probe trajectory data to estimate queue length. With the emergence of CV technology, probe trajectory data is more valuable because it comprises the same types of data as CVs provide, such as the vehicle identification, speed, time and location. The researchers developed a data structure, including probe trajectory data generated in VISSIM and estimated data based on timings, to determine queue length. In order to examine accuracy of queue length estimation under different market penetration rates, an intersection in Palo Alto, California was simulated for an hour in VISSIM and different percentages of vehicles were randomly tracked to provide trajectory data for estimation. When the simulation was running under a 100% penetration rate, trajectory data from 100% vehicles was used to determine queue length, which was considered as the ground truth queue length. By comparing the estimated queue length under lower penetration rates with the ground truth queue length, Mean Absolute Percentage Errors (MAPEs) were developed, based on the formula below, to evaluate estimation accuracy. The research verified that using probe vehicles helped achieve good estimation accuracy when measuring queue lengths.

$$MAPE = \frac{1}{n}\sum_{n}\left|\frac{estimated\ value - ground\ truth}{ground\ truth}\right|$$

Where n is the number of cycles within an hour.

MAPEs under different CV market penetration rates were summarized in Table 1.

Table 1. MAPE in queue length estimation developed using probe trajectory data

Penetration rate	MAPE
90%	4.29%
80%	6.35%
70%	11.35%
60%	14.26%
50%	17.27%
40%	24.95%
30%	29.80%
20%	42.15%
10%	60.85%

This data could be used in determining the minimum CV penetration rate required for the proposed application. For example when CVs have a penetration rate of 90%, it can be expect that the queue length will be accurate to within 4.92% as either shorter or longer than the actual length.

2.4 SUMMARY

It is worth noting that all of the current research using connected vehicle data to design control strategies is for an isolated intersection. There is no research on coordinated signal timing improvement through CV V2I communications. In addition, most studies use the queue length as a parameter in determining the optimized control operation. Based on the literatures, a viable methodology to estimate queue length is based on the location and stopping time of the last connected vehicle in queue and the following unequipped vehicles are added to the calculation of queue length at the previous arrival rate. Probe vehicle trajectory data is very useful in queue length estimation and the developed MAPE data was used by the researchers in Section 3.5 & 4.4.

3.0 APPROACH FOR TESTING THE HYPOTHESIS

The testing approach involves using traffic operation simulation models and conducting a comparative analysis. This chapter gives the detailed information on how the testing models were developed, and how the simulation results reported under different traffic scenarios were compared and analyzed in order to test the hypothesis.

3.1 INTRODUCTION

The key to realizing the benefits of improved coordinated operation is to base offset calculations on actual queue length data available from connected vehicles. Based on the traffic principles, a method was developed to test the hypothesis in the simulation environment. In addition, a statistical estimation was conducted to identify the minimum CV market penetration rate in the traffic stream required to improve performance.

3.2 THEORY AND EQUATION

Queue length is the primary variable and has been intensively studied to determine offsets. The following section explains the method to estimate queue length at signals and determine timing offset used in this research.

3.2.1 Queue length

Queue length at signals is the distance between the stop line and the back bumper of the last vehicle in queue. Queue would vary based on many factors, such as analysis period, volume level, geometry, signal timings and driver behavior. Traditionally queue length is estimated by using data collected from loop detectors, but the installation and maintenance of loop detectors is costly. There is always a lack of data in estimating queue length at most intersections around the United States.

In the research it was assumed that queue length has been available from CV technology and queue length provided by a simulation program was used to improve timing offset.

3.2.2 Timing offset

In coordinated systems, green times for signals are adjusted to allow vehicles to efficiently move through the set of signals. Timing offset is the difference between the two green initiation times, influenced by distance between signals, vehicular speed and the effect of queued vehicles at the downstream intersection. Properly accounting for downstream queue lengths is critical in the determination of correct offsets in the signal retiming process. Currently it is difficult to accurately know the queue length per cycle at a signal. With the development of connected vehicle technologies it will be possible to have a more accurate queue length and know how it varies over a time period. Offset for coordinated signals could be calculated using a basic equation [Roess et al., 2011] as follow:

$$offset\ (s) = \frac{D}{S} - (Nh + \ell_1)$$

Where:

D=distance between signals, ft

S=speed, ft/s

N=number of vehicles queued per lane, veh

h=discharge headway of queued vehicles, s/veh

ℓ_1=start-up lost time, s

Besides queue length, the researchers could obtain link distance and vehicular speed of progression for the testing roadway network. The number of queued vehicles was determined by dividing the queue length by the average headway between vehicles. The researchers set a common value 2 seconds as the average start-up lost time and assumed that the average discharge headway of queued vehicle is equal to a saturation headway of 1.9 seconds, which corresponds to a common saturation flow rate of 1,900 vehicles per hour per lane. These are standard factors used in calculations for vehicle performance.

3.3 DEVELOPMENT OF METHODOLOGY

In order to test the hypothesis the researchers collected Synchro traffic models for test networks, which includes current traffic signal operating plans, existing TOD timing plans, traffic volumes during the specified TOD plan operations and other data required for model development. The Synchro models were imported to VISSIM for simulations of three traffic scenarios: traffic under existing coordinated TOD timings operation (scenario 1), improved coordinated timing operation with offsets developed by Synchro (scenario 2), and improved timings operation with alternative offsets determined using the queue measurements from SimTraffic (scenario 3). This third scenario simulates the impact of using CV information for determining more accurate offsets. The Figure 2 below illustrates this approach process.

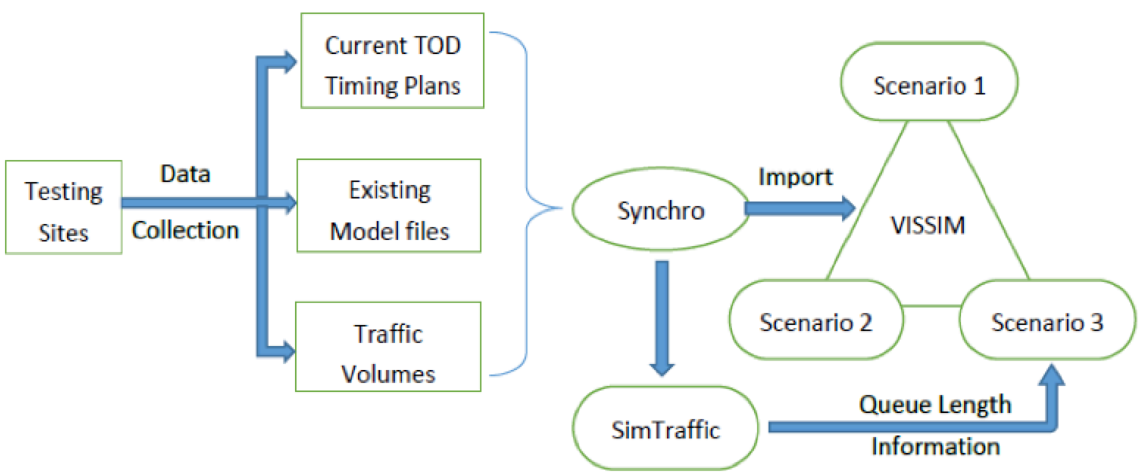

Figure 1. The illustration of testing methodology used in the research

3.4 TESTING THE HYPOTHESIS

This section describes the test corridor networks, data collection and development process of the traffic models under the three scenarios in VISSIM.

3.4.1 Test sites

Two corridor networks were considered as the test sites. They are representative of two different types of corridors, including a suburban highway corridor and an urban/city street network. The researcher performed traffic operation simulations and tested the hypothesis for both the two networks. Table 2 summarizes the two road networks.

Table 2. The summary table of the two test corridor networks

Network	*Owner*	*Number of Intersections*	*Current Control Type*	*Characteristic*
US Route 22	Penn DOT	9	ASCT	US highway, Long distance between neighboring intersections
Baum-Centre Corridor	City of Pittsburgh	11	ASCT	City street, Dense roadway network, more balanced volume patterns

3.4.1.1 U.S. Route 22

US Route 22 is an east-west route that crosses into Pennsylvania as the William Penn Highway. A section of the William Penn Highway in the Municipality of Murrysville was considered as the study corridor network. An adaptive signal control system is currently being installed at eleven intersections along this section of the route. The Synchro model for the corridor network is available from the municipality. The figures 2 and 3 below present the range of the potential corridor network.

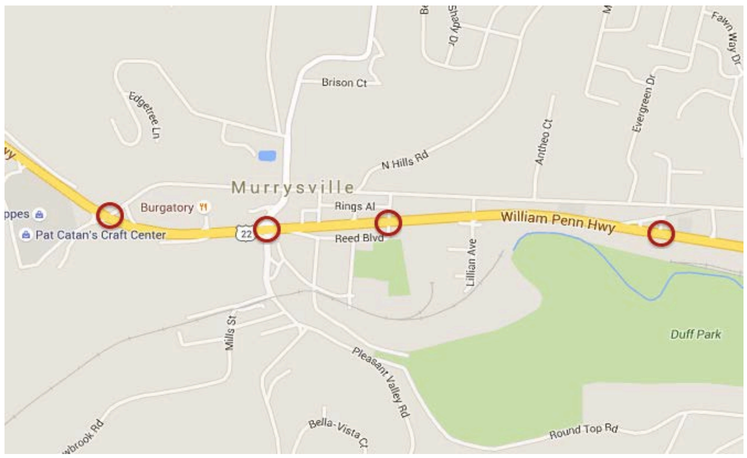

Figure 2. The study segment of U.S. Route 22 in Murrysville, Pennsylvania (part a)

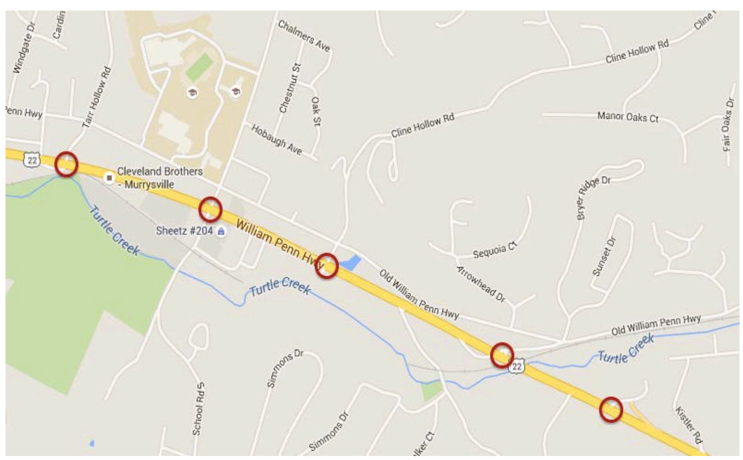

Figure 3. The study segment of U.S. Route 22 in Murrysville, Pennsylvania (part b)

3.4.1.2 Baum-Centre corridor in Pittsburgh, PA

Baum Boulevard and Centre Avenue are parallel east-west major arterials in the City of Pittsburgh. They form an urban corridor network that serves the surrounding communities. A section of the corridor network (shown in Figure 4) was selected as the testing site. The owner of the system can provide the required traffic data and Synchro files for the corridor network.

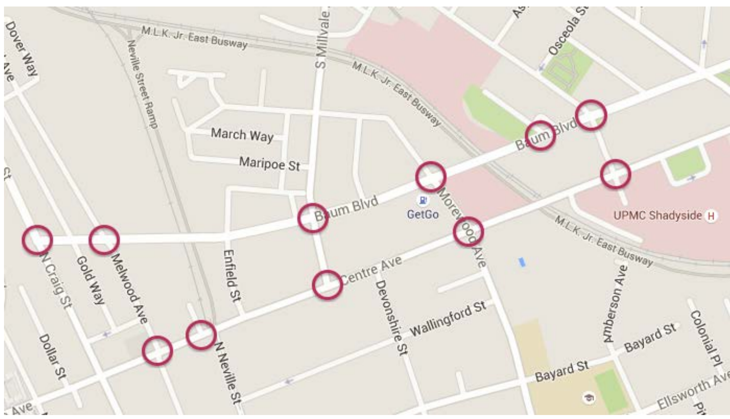

Figure 4. A segment of Baum-Centre corridor in the city of Pittsburgh, Pennsylvania

3.4.2 Data collection

The required data for the simulations includes traffic volumes, queue lengths and timing plans for the three corridor networks. The following states how the input data for VISSIM was collected.

3.4.2.1 Traffic volumes

The peak hours (AM peak 7:30-8:30, Mid-day peak 1:30-2:30 and PM peak 2:30-3:30) was determined from the ATR (Automatic Traffic Recorder) counts. Traffic movement counts at intersections were conducted during the study peak periods in April of 2013 for William Penn Highway and in February of 2013 for Baum-Centre corridor network. The researchers directly used the peak hour data included in the Synchro files for traffic simulations.

3.4.2.2 Timing plans

Existing time-of-day (TOD) timing plans for signals in the two corridor networks were obtained from the City of Pittsburgh and PennDOT. The William Penn Highway is currently running an adaptive signal control system but at that time of data collection a TOD plan was running. The pervious TOD plan was used for scenario 1. The Baum-Centre corridor is currently running an adaptive plan however the recently optimized TOD plan was used for scenario 1.Because this research focused on the retiming strategy of coordinated TOD timing plans, the real-time timings created by adaptive control systems were not used.

3.4.2.3 Queue length

The research methodology was to simulate a scenario that connected vehicles are running in a corridor. Because in real traffic conditions location and stopping time of each vehicle at signals is unavailable due to the limitation of current data collection technologies, the researcher simulated the CV information by SimTraffic, which determines queue lengths by lane. According to Trafficware software Manual [Trafficware, 2014], SimTraffic would be a more realistic representation than Synchro because the queue length is an average of all the two-minute maximum queues reported in SimTraffic. The SimTraffic simulated queues were used in the scenario 3 analysis.

The measurement of queues in auxiliary lanes was not used to determine the optimal offset. Because on those testing sites, signal coordination is designed to enhance the operation of directional movements along the arterial road, projected offsets only reflect vehicles making through movement on competing approaches.

For roadway links with strong directional distributions, queues traveling in the peak direction of flow were taken to optimize timing offsets. If there was bidirectional demand on a road, queue length was adjusted according for the proportion of traffic in two directions. In the determination of queue length on an approach, average queue length was taken between through lanes and shared lanes (through plus left or right lane); the larger queue length was taken between through lanes.

For meaningful results, five simulation runs were performed in SimTraffic. Average queue length and speed of progression for each node are summarized in Appendix.

3.4.3 Model development

The traffic models was carefully developed in Synchro and then transferred to VISSIM because VISSIM can create a more valid simulation environment for Measures of Effectiveness (MOE) for results comparison. In order to explore performance with the different scenario signal timings, for either road network the researchers used the same traffic volumes to perform model simulations for the three timing scenarios as described in the followings.

Optimal signal timings produced by Synchro was used in the Scenario 2 model development. Because many traffic engineers use the Synchro optimization model when retiming signals, this represents current typical practice. In Scenario 3, the researchers then evaluated the operation of the signal timing plans produced using simulated CV data, in VISSIM. The development of the three scenarios as well as the relevant data used in every phase of the process is illustrated in Figure 5.

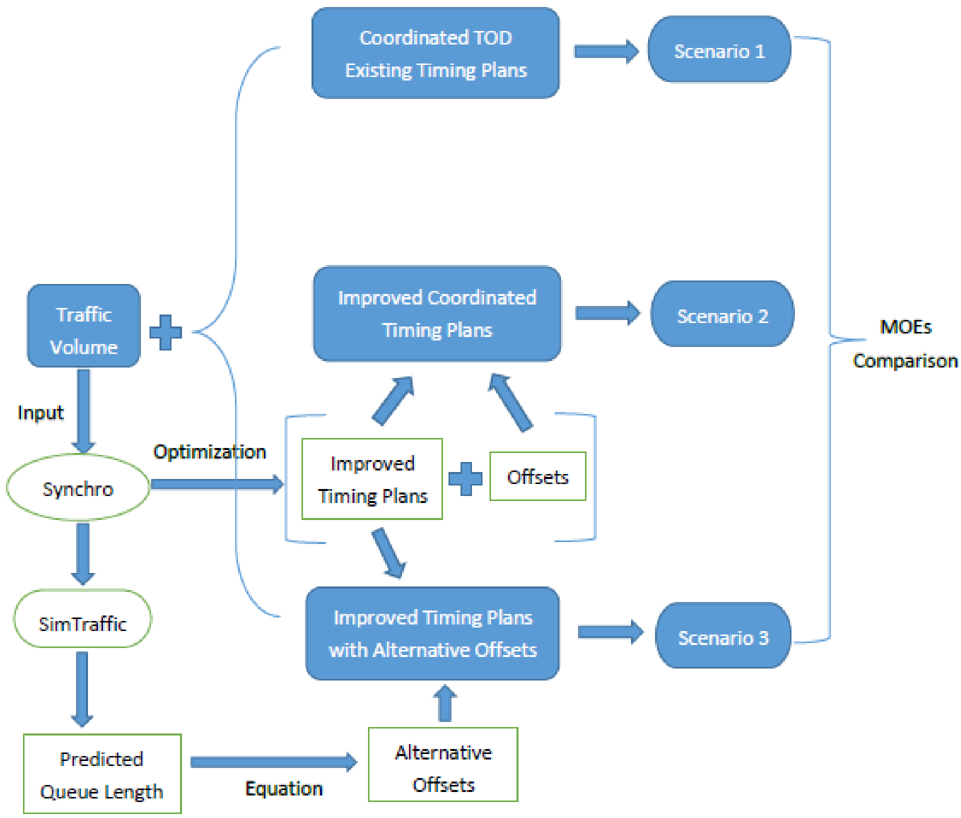

Figure 5. The flow diagram of development of the traffic scenarios

3.4.3.1 Scenario I: Coordinated TOD timings traffic operation

In this scenario, both the road networks are operating with the existing TOD timing plans. Timing settings follow the current timing plan sheets from PennDOT or the City of Pittsburgh. For simulation, offsets and timings as well as the collected traffic volumes were input into the well-developed models in Scenario 1.

3.4.3.2 Scenario II: Improved coordinated traffic operation

New coordinated TOD timing plans, which are optimized by Synchro based on current traffic volumes collected as part of this research, were simulated in Scenario 2. Synchro's optimization algorithms determined the offsets with the lowest delays by an iterative incremental method. It evaluates the control delays and varies the offset around the cycle length closest to the lowest delays for the system in the Synchro simulation environment.

3.4.3.3 Scenario III: Improved traffic operation with alternative offsets

This scenario is based upon the assumption that CV information that will be available once there is a significant degree of connected vehicles in the traffic stream can provide a more accurate queue length. Compared with Scenario 2, the only difference is the new offsets determined using the simulated CV queue length information in Scenario 3. The researchers used the queue length information from SimTraffic to create the condition of scenario 3. Then the equation described in section 3.2.2 was used to calculate offsets based on the queue length information, defined as 'SimTraffic predicted queue length'. Optimal timing offsets for signals are summarized in Appendix A. The effectiveness of the signal operation with the calculated offsets and the collected traffic volumes was simulated in the scenario.

3.5 DETERMINING THE REQUIRED CV PENETRATION RATE

If most vehicles are equipped with CV devices, a traffic controller can be designed to operate quite efficiently and provide efficient timings for each vehicle at the intersection. This is because individual vehicle movements could be tracked and accommodated in the timing algorithm. If the research results show that performance of coordinated signal timings is improved by this queue length information, the researchers would determine at what penetration rate of connected vehicles in the traffic stream, accuracy of estimated queue length is acceptable to optimize timing offset and improve coordinated traffic signal systems.

According to the literature reviews in Chapter 2, MAPE (Mean Absolute Percentage Error) of queue length estimation has been developed [Li et al., 2013] based on simulation results in VISSIM. In this research the queue length from SimTraffic was assumed to be the true queue length. The researchers determined boundaries of estimated queue lengths (the possible lowest and highest values) under a CV market penetration rate based on the corresponding MAPE shown in Table 1, used the boundary values to try in VISSIM, and saw if the simulation results are positive with the queue length information.

3.6 SUMMARY

Full details of the research testing approach were described in the chapter. The researchers identified the equation used to determine optimal offsets and constructed a framework including three traffic scenarios for analysis. Two testing corridor networks were selected and all relevant data and traffic models were prepared for simulation in VISSIM. The methodology to determine the required CV penetration rate was also identified.

4.0 TEST RESULTS

The chapter presents the VISSIM simulation results and result analysis for the two test corridor networks. This has been used to draw conclusions on whether the use of queue length information available from connected vehicles could improve signal timing coordination for corridors and how to incorporate queue length information into future signal retiming operations.

4.1 INTRODUCTION

The following details operation performance of the test corridor networks under the three different traffic scenarios. Several traffic Measures of Effectiveness (MOEs) generated by VISSIM were selected to quantify performance of control operations, including average delay per vehicle and average number of stops per vehicle in the roadway networks, the Highway Capacity Manual (HCM) Level of Service (LOS) at signalized intersections along the test corridors and average travel time for vehicles to run through the corridor networks. All the MOEs were compared and analyzed for each study time period and the traffic scenario in order to test the hypothesis.

4.2 SIMULATION RESULTS

VISSIM simulated traffic and signal control in the three scenarios for the two corridors and output their complete network performance. The period of time to be simulated was 4500 seconds, or 75minutes, which includes a 15-minute initialization period and 1 hour of simulation. For every traffic scenario during each time period, the arithmetic mean of the MOEs was determined based on the results of three simulation runs with identical input files and different random seed settings.

4.2.1 William Penn Highway network

There are nine intersections along William Penn Highway in the test network. For the sake of convenience the researchers numbered the remaining 9 intersections, as shown in Table 3.

Table 3. The numbered roadway intersections in the William Penn Hwy network

Number	Intersection
1	Private Dr/Old Wm Penn Hwy & William Penn Hwy/SR 22
2	Traffordl/Vincent Hall Rd & SP 22/William Penn Hwy
3	Reed Ave/Gates Ave & William Penn Hwy
4	William Penn Hwy & Branthoover Cutoff
5	Tarr Hollow Rd & William Penn Hwy
6	School Rd & William Penn Hwy
7	Cline Hollow Rd & William Penn Hwy
8	William Penn Hwy & Cozy Inn Cut Off
9	William Penn Hwy & Triangle Ln

In Scenario 1, traffic signals along William Penn Highway were operating under the existing TOD timings operation. During the AM peak hour, 4,636 vehicles had already reached their destination that traveled through the network, and have left the network before the end of the simulation. Vehicles arrived was used as an MOE because it describes how efficient the network is in processing vehicles in the simulation period. The average number of stops per vehicle that was in the network or had already arrived was 4.58 seconds and the average standstill time per vehicle was 39.14 seconds. Within the hour the average delay per vehicle that was in the network or had already arrived is 90.25 seconds. The network performance MOEs are presented in Table 4.

Table 4. William Penn Hwy network performance MOEs in Scenario 1

TimePeriod	DelayAvg/vehicle (sec)	StopsAvg/vehicle	DelayStopAvg/vehicle (sec)	Vehicles(arrived)
AM peak	90.25	4.58	39.14	4,636
MD hour	61.70	4.22	30.28	4,555
PM peak	141.06	4.83	58.11	5,706

By measuring delay times in the VISSIM node evaluation, the researchers also determined the LOS (Level of Service) for each intersection. The LOS of intersections in the test network is presented in Table 5.

Table 5. LOSs of the intersections along William Penn Hwy in Scenario 1

Intersection #.	1	2	3	4	5	6	7	8	9
AM LOS	D	E	B	A	B	C	B	A	A
MD LOS	D	D	B	A	B	C	B	A	A
PM LOS	E	E	B	A	B	C	C	B	A

The researchers also defined a vehicle travel time measurement in the VISSIM simulation, which is the average travel time from one end of the corridor to the other end. Travel time of a vehicle was recorded in VISSIM if the vehicle traveled through the completed corridor in either direction in the network. The number of vehicles recorded and their average travel time are presented in Table 6.

Table 6. Average travel time of vehicles in the William Penn Hwy network in Scenario 1

		Vehicles	Travel Time (sec)
AM peak	Eastbound	512	428.73
	Westbound	513	540.52
MD hour	Eastbound	552	450.85
	Westbound	482	444.40
PM peak	Eastbound	582	685.91
	Westbound	512	525.70

In Scenario 2, traffic signals along William Penn Highway were operating under the improved coordinated timing operation with offsets developed by Synchro. During the AM peak hour, 4,637 vehicles had already reached their destination and have left the network before the end of the simulation. The average number of stops per vehicle that was in the network or had already arrived was 4.02 seconds and the average standstill time per vehicle was 35.33 seconds.

Within the hour the average delay per vehicle that was in the network or had already arrived is 79.52 seconds. The network performance MOEs are presented in Table 7.

Table 7. William Penn Hwy network performance MOEs in Scenario 2

TimePeriod	DelayAvg/vehicle (sec)	StopsAvg/vehicle	DelayStopAvg/vehicle (sec)	Vehicles(arrived)
AM peak	79.52	4.02	35.33	4,637
MD hour	54.45	3.64	28.63	4,531
PM peak	132.83	4.13	53.23	5,876

By measuring delay times in the VISSIM node evaluation, the researchers also determined the LOS (Level of Service) for each intersection. The LOS of intersections in the test network is presented in Table 8.

Table 8. LOSs of the intersections along William Penn Hwy in Scenario 2

Intersection #.	1	2	3	4	5	6	7	8	9
AM LOS	D	E	C	B	C	D	C	C	B
MD LOS	D	D	C	B	B	D	C	B	C
PM LOS	D	F	D	A	B	D	C	B	B

The researchers also defined a vehicle travel time measurement in the VISSIM simulation, which is the average travel time from one end of the corridor to the other end. Travel time of a vehicle was recorded in VISSIM if the vehicle traveled through the completed corridor in either direction in the network. The number of vehicles recorded and their average travel time are presented in Table 9.

Table 9. Average travel time of vehicles in the William Penn Hwy network in Scenario 2

		Vehicles	Travel Time (sec)
AM peak	Eastbound	521	409.43
	Westbound	538	463.80
MD hour	Eastbound	552	393.96
	Westbound	479	416.79
PM peak	Eastbound	711	457.12
	Westbound	500	489.96

In Scenario 3, traffic signals along William Penn Highway were operating under the improved timings operation with alternative offsets determined using the queue measurements. During the AM peak hour, 4,645 vehicles had already reached their destination and have left the network before the end of the simulation. The average number of stops per vehicle that was in the network or had already arrived was 3.73 seconds and the average standstill time per vehicle was 37.29 seconds. Within the hour the average delay per vehicle that was in the network or had already arrived is 72.22 seconds. The network performance MOEs are presented in Table 10.

Table 10. William Penn Hwy network performance MOEs Scenario 3

TimePeriod	DelayAvg/vehicle (sec)	StopsAvg/vehicle	DelayStopAvg/vehicle (sec)	Vehicles(arrived)
AM peak	72.22	3.73	37.29	4,645
MD hour	58.12	3.86	30.62	4,539
PM peak	124.72	3.87	52.52	5,858

By measuring delay times in the VISSIM node evaluation, the researchers also determined the LOS (Level of Service) for each intersection. The LOS of intersections in the test network is presented in Table 11.

Table 11. LOSs of the intersections along William Penn Hwy in Scenario 3

Intersection #.	1	2	3	4	5	6	7	8	9
AM LOS	D	E	C	B	B	D	C	C	C
MD LOS	D	D	C	B	B	D	C	B	C
PM LOS	D	F	D	A	B	D	C	B	B

The researchers also defined a vehicle travel time measurement in the VISSIM simulation, which is the average travel time from one end of the corridor to the other end. Travel time of a vehicle was recorded in VISSIM if the vehicle traveled through the completed corridor in either direction in the network. The number of vehicles recorded and their average travel time are presented in Table 12.

Table 12. Average travel time of vehicles in the William Penn Hwy network in Scenario 1

		Vehicles	Travel Time (sec)
AM peak	Eastbound	503	387.53
	Westbound	532	423.97
MD hour	Eastbound	561	416.07
	Westbound	476	419.19
PM peak	Eastbound	697	442.73
	Westbound	507	475.77

4.2.2 Baum-Centre corridor Network

There are 11 intersections in the test section of Baum-Centre corridor network. For the sake of convenience the researchers numbered every intersection, as shown in Table 13.

Table 13. The numbered roadway intersections in the Baum-Centre corridor network

Number	Intersection
100	Craig St & Baum Blvd
105	Melwood Ave & Baum Blvd
110	Millvale Ave & Baum Blvd
115	Morewood Ave & Baum Blvd
116	Luna Parking Garage & Baum Blvd
120	Cypress St & Baum Blvd
205	Melwood Ave & Centre Ave
210	Neville St & Centre Ave
215	Millvale Ave & Centre Ave
220	Morewood Ave & Centre Ave
225	Cypress St & Centre Ave

In Scenario 1, traffic signals along the test segment of Baum-Centre Corridor were operating under the existing TOD timings operation. During the AM peak hour, 4,673 vehicles had already reached their destination and have left the network before the end of the simulation. The average number of stops per vehicle that was in the network or had already arrived was 3.94 seconds and the average standstill time per vehicle was 78.63 seconds. Within the hour the average delay per vehicle that was in the network or had already arrived is 110.4 seconds. The network performance MOEs are presented in Table 14.

Table 14. Baum-Centre corridor network performance in Scenario 1

TimePeriod	DelayAvg/vehicle (sec)	StopsAvg/vehicle	DelayStopAvg/vehicle (sec)	Vehicles(arrived)
AM peak	110.4	3.94	78.63	4,673
MD hour	44.14	1.47	30.32	3,206
PM peak	154.29	3.78	106.15	4,323

By measuring delay times in the VISSIM node evaluation, the researchers also determined the LOS (Level of Service) for each intersection. The LOS of intersections in the test network is presented in Table 15.

Table 15. LOSs of the intersections along Baum-Centre Corridor in Scenario 1

AM peak	Baum Int. #.	100	105	110	115	116	120
	LOS	B	E	C	C	B	C
	Centre Int. #.	205	210	215	220	225	
	LOS	C	C	C	C	C	
MD hour	Baum Int. #.	100	105	110	115	116	120
	LOS	B	C	B	B	A	B
	Centre Int. #.	205	210	215	220	225	
	LOS	B	C	C	C	C	
PM peak	Baum Int. #.	100	105	110	115	116	120
	LOS	C	F	E	E	C	C
	Centre Int. #.	205	210	215	220	225	
	LOS	D	F	D	D	D	

The researchers also defined a vehicle travel time measurement in the VISSIM simulation, which is the average travel time from one end of the corridor to the other end. Travel time of a vehicle was recorded in VISSIM if the vehicle traveled through the completed corridor in either direction in the network. The number of vehicles recorded and their average travel time are presented in Table 16.

Table 16. Average travel time of vehicles in the Baum-Centre Corridor network in Scenario 1

AM peak	***Baum Blvd***	Vehicles	Travel Time (sec)
	Eastbound	253	145.12
	Westbound	505	129.36
	Centre Ave	Vehicles	Travel Time (sec)
	Eastbound	85	172.02
	Westbound	113	207.96
MD hour	***Baum Blvd***	Vehicles	Travel Time (sec)
	Eastbound	221	101.80
	Westbound	256	107.66
	Centre Ave	Vehicles	Travel Time (sec)
	Eastbound	85	158.21
	Westbound	113	148.95
PM peak	***Baum Blvd***	Vehicles	Travel Time (sec)
	Eastbound	253	145.12
	Westbound	505	129.36
	Centre Ave	Vehicles	Travel Time (sec)
	Eastbound	85	172.02
	Westbound	113	207.96

In Scenario 2, traffic signals along the test segment of Baum-Centre Corridor were operating under the improved coordinated timing operation with offsets developed by Synchro. During the AM peak hour, 4,240 vehicles had already reached their destination and have left the network before the end of the simulation. The average number of stops per vehicle that was in the network or had already arrived was 2.98 seconds and the average standstill time per vehicle was 67.75 seconds. Within the hour the average delay per vehicle that was in the network or had already arrived is 109.29 seconds. The network performance MOEs are presented in Table 17.

Table 17. Baum-Centre Corridor network performance in Scenario 2

TimePeriod	DelayAvg/vehicle (sec)	StopsAvg/vehicle	DelayStopAvg/vehicle (sec)	Vehicles(arrived)
AM peak	109.29	2.98	67.75	4,240
MD hour	42.82	1.68	26.38	3,201
PM peak	145.30	3.68	97.18	4,382

By measuring delay times in the VISSIM node evaluation, the researchers also determined the LOS (Level of Service) for each intersection. The LOS of intersections in the test network is presented in Table 18.

Table 18. LOSs of the intersections along Baum-Centre Corridor in Scenario 2

<table>
<tr><td rowspan="4">AM peak</td><td>Baum Int. #.</td><td>100</td><td>105</td><td>110</td><td>115</td><td>116</td><td>120</td></tr>
<tr><td>LOS</td><td>B</td><td>E</td><td>C</td><td>C</td><td>B</td><td>C</td></tr>
<tr><td>Centre Int. #.</td><td>205</td><td>210</td><td>215</td><td>220</td><td>225</td><td></td></tr>
<tr><td>LOS</td><td>C</td><td>C</td><td>D</td><td>D</td><td>D</td><td></td></tr>
<tr><td rowspan="4">MD hour</td><td>Baum Int. #.</td><td>100</td><td>105</td><td>110</td><td>115</td><td>116</td><td>120</td></tr>
<tr><td>LOS</td><td>B</td><td>B</td><td>B</td><td>B</td><td>A</td><td>B</td></tr>
<tr><td>Centre Int. #.</td><td>205</td><td>210</td><td>215</td><td>220</td><td>225</td><td></td></tr>
<tr><td>LOS</td><td>B</td><td>B</td><td>B</td><td>C</td><td>B</td><td></td></tr>
<tr><td rowspan="4">PM peak</td><td>Baum Int. #.</td><td>100</td><td>105</td><td>110</td><td>115</td><td>116</td><td>120</td></tr>
<tr><td>LOS</td><td>C</td><td>F</td><td>D</td><td>D</td><td>B</td><td>B</td></tr>
<tr><td>Centre Int. #.</td><td>205</td><td>210</td><td>215</td><td>220</td><td>225</td><td></td></tr>
<tr><td>LOS</td><td>D</td><td>E</td><td>D</td><td>D</td><td>D</td><td></td></tr>
</table>

The researchers also defined a vehicle travel time measurement in the VISSIM simulation, which is the average travel time from one end of the corridor to the other end. Travel time of a vehicle was recorded in VISSIM if the vehicle traveled through the completed corridor in either direction in the network. The number of vehicles recorded and their average travel time are presented in Table 19.

Table 19. Average travel time of vehicles in the Baum-Centre Corridor network in Scenario 2

AM peak	***Baum Blvd***	Vehicles	Travel Time (sec)
	Eastbound	249	122.22
	Westbound	528	125.14
	Centre Ave	Vehicles	Travel Time (sec)
	Eastbound	85	222.43
	Westbound	108	317.45
MD hour	***Baum Blvd***	Vehicles	Travel Time (sec)
	Eastbound	205	105.86
	Westbound	259	107.28
	Centre Ave	Vehicles	Travel Time (sec)
	Eastbound	120	163.92
	Westbound	109	140.15
PM peak	***Baum Blvd***	Vehicles	Travel Time (sec)
	Eastbound	431	355.78
	Westbound	322	146.37
	Centre Ave	Vehicles	Travel Time (sec)
	Eastbound	101	414.08
	Westbound	110	198.05

In Scenario 3, traffic signals along the test segment of Baum-Centre Corridor were operating under the improved timings operation with alternative offsets determined using the queue measurements. During the AM peak hour, 4,249 vehicles had already reached their destination and have left the network before the end of the simulation. The average number of stops per vehicle that was in the network or had already arrived was 2.81 seconds and the average standstill time per vehicle was 61.02 seconds. Within the hour the average delay per vehicle that was in the network or had already arrived is 94.61 seconds. The network performance MOEs are presented in Table 20.

Table 20. Baum-Centre Corridor network performance in Scenario 3

TimePeriod	DelayAvg/vehicle (sec)	StopsAvg/vehicle	DelayStopAvg/vehicle (sec)	Vehicles(arrived)
AM peak	94.61	2.81	61.02	4,249
MD hour	44.85	1.75	28.16	3,202
PM peak	113.87	3.17	76.28	4,416

By measuring delay times in the VISSIM node evaluation, the researchers also determined the LOS (Level of Service) for each intersection. The LOS of intersections in the test network is presented in Table 21.

Table 21. LOSs of the intersections along Baum-Centre Corridor in Scenario 3

AM peak	Baum Int. #.	100	105	110	115	116	120
	LOS	B	E	D	C	B	B
	Centre Int. #.	205	210	215	220	225	
	LOS	C	C	D	D	C	
MD hour	Baum Int. #.	100	105	110	115	116	120
	LOS	B	B	B	B	B	B
	Centre Int. #.	205	210	215	220	225	
	LOS	B	B	B	C	B	
PM peak	Baum Int. #.	100	105	110	115	116	120
	LOS	B	E	D	D	D	C
	Centre Int. #.	205	210	215	220	225	
	LOS	D	E	D	D	D	

The researchers defined a vehicle travel time measurement in the VISSIM simulation, which is the average travel time from one end of the corridor to the other end. Travel time of a vehicle was recorded in VISSIM if the vehicle traveled through the completed corridor in either direction in the network. The number of vehicles recorded and their average travel time are presented in Table 22.

Table 22. Average travel time of vehicles in the Baum-Centre Corridor network in Scenario 3

AM peak	***Baum Blvd***	Vehicles	Travel Time (sec)
	Eastbound	249	124.05
	Westbound	537	138.98
	Centre Ave	Vehicles	Travel Time (sec)
	Eastbound	87	198.89
	Westbound	109	227.85
MD hour	***Baum Blvd***	Vehicles	Travel Time (sec)
	Eastbound	204	122.08
	Westbound	259	125.06
	Centre Ave	Vehicles	Travel Time (sec)
	Eastbound	123	155.45
	Westbound	100	154.57
PM peak	***Baum Blvd***	Vehicles	Travel Time (sec)
	Eastbound	470	169.31
	Westbound	320	219.54
	Centre Ave	Vehicles	Travel Time (sec)
	Eastbound	110	417.98
	Westbound	113	164.10

4.3 ANALYSIS OF RESULTS

The output data in VISSIM were compared among the three traffic scenarios for each test corridor network. Because the test results seem to be significantly positive only in the peak hours, the researchers evaluated how CV data benefited signal control operation only during peak hours and not off-peak hours.

4. 3. 1 **Efficiency in Peak Hours**

During the peak hours the test results substantially support the hypothesis. The network performance was largely improved when the queue measurements were used in the signal retiming.

4.3.1.1 Network performance

Compared with the existing timings operation, the Synchro optimized timings operation reduced the average delay in the William Penn Highway network by 10.7 seconds and 8.2 seconds per vehicle during AM and PM peaks, and by 1.1 seconds and 9.3 seconds per vehicle during the same two study time periods in the Baum-Centre Corridor network.

While the timings operation improved by Synchro, with optimal offsets determined using the queuing formation, reduced average delay per vehicle in the William Penn Highway network by 18 seconds and 16.3 second per vehicle during AM and PM peaks when the existing TOD timings were replaced with the Synchro optimal timings and the optimized offsets using the queue measurements. In the same circumstance there were reductions of 15.8 second and 40.7 second in average delay per vehicle in the Baum-Centre Corridor network.

When compared to the Synchro optimized timing operation, the developed timing offsets helped reduce average delay by 9.2% and 6.1% during the AM and PM peak in the William Penn Highway network, and by 13.4% and 21.6% during the two peak hours in the Baum-Centre Corridor network.

In the two peak hours, average delay per vehicle under the three different signal timing operations were compared in Figure 6 & 7 for the William Penn Highway network, in Figure 8 & 9 for the Baum-Centre Corridor network.

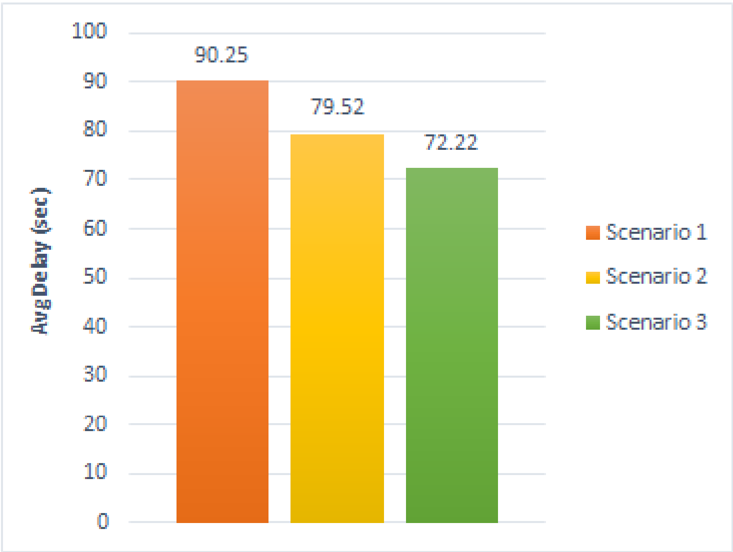

Figure 6. Average delay per vehicle in the William Penn Highway network during AM peak

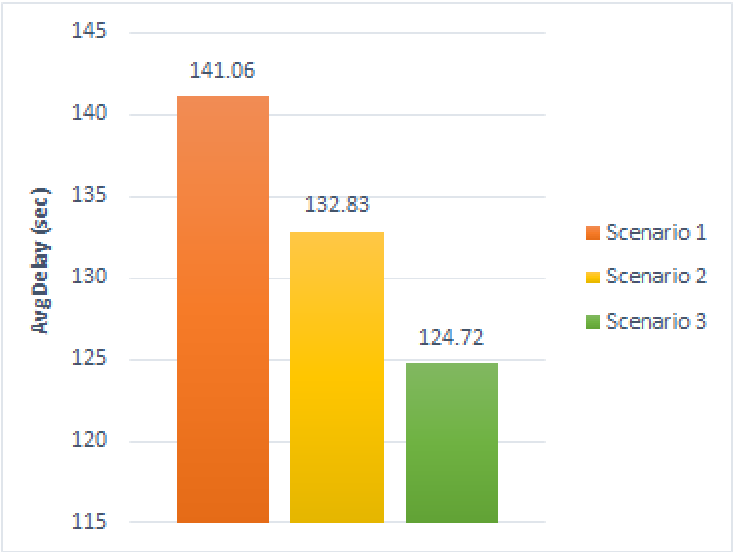

Figure 7. Average delay per vehicle in the William Penn Highway network during PM peak

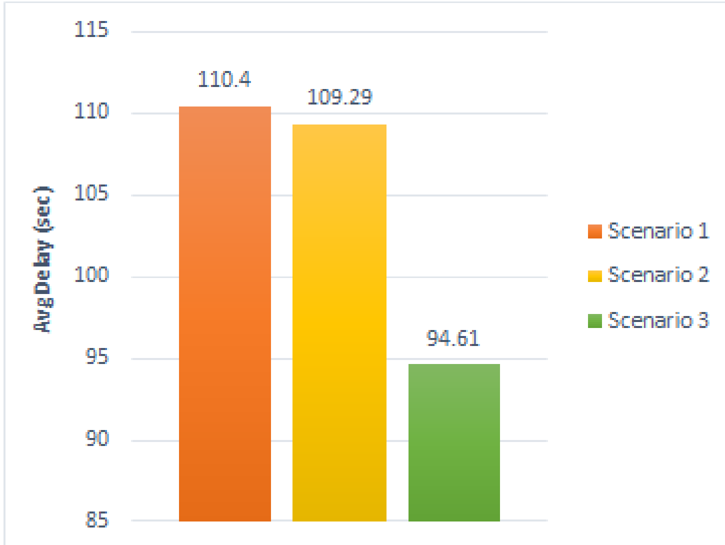

Figure 8. Average delay per vehicle in the Baum-Centre Corridor network during AM peak

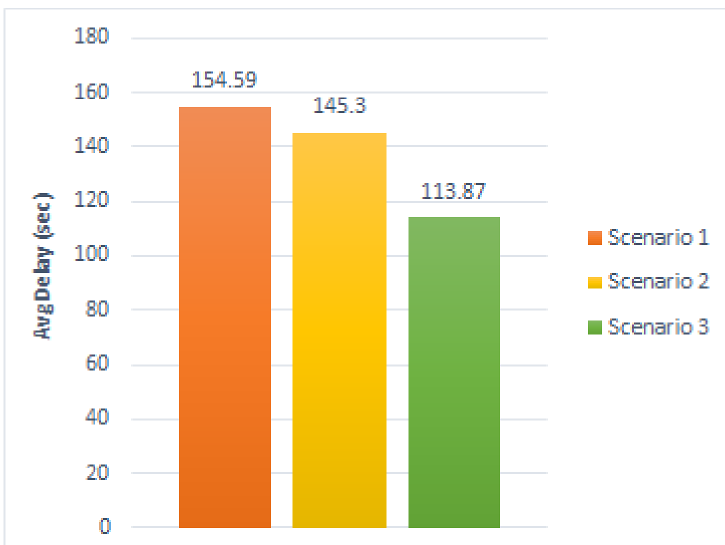

Figure 9. Average delay per vehicle in the Baum-Centre Corridor network during PM peak

The number of stops of vehicles running in the test networks was also measured in simulations. On average, a vehicle stopped 4.58 times in the AM peak and 4.83 times in the PM peak in the William Penn Highway network under the existing timings operation. When the signals were retimed by Synchro in the simulation, the vehicle on average stopped 4.02 times, 0.56 times less, in the AM peak and stopped 4.13 times, 0.7 times less, in the PM peak.

When the offsets were optimized using the queuing information, the vehicle only stopped 3.73 times in the AM peak, 0.85 times less than the original scenario 1 average stops, and stopped 3.87 times in the PM peak, almost 1 time less than the original average stops.

Compared with vehicles under the Synchro optimized timing operation, the average number of stops of vehicles under the operation with the optimal offsets decreased by 7.2% and 6.3% during the AM and PM peak in the William Penn Highway network, and by 5.7% and 13.9% during the two peak hours in the Baum-Centre Corridor network.

Figure 10 & 11 below show the change in average number of stops in the William Penn Highway network under the three different signal operations during peak hours.

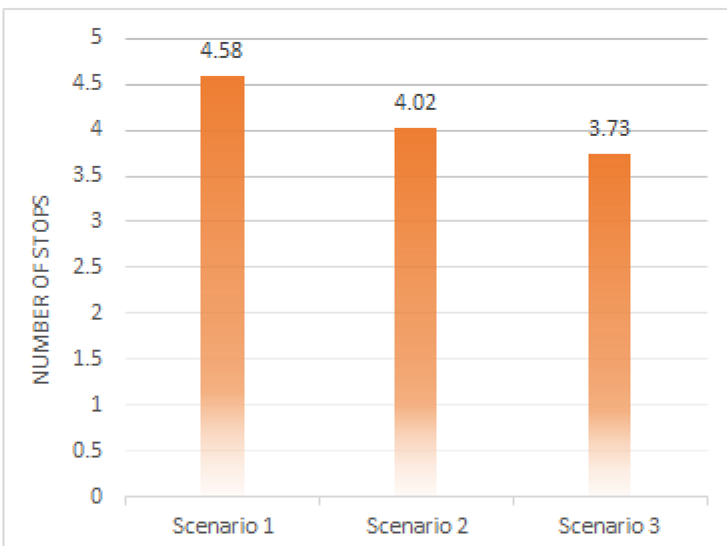

Figure 10. Average number of stops in the William Penn Highway network during AM peak

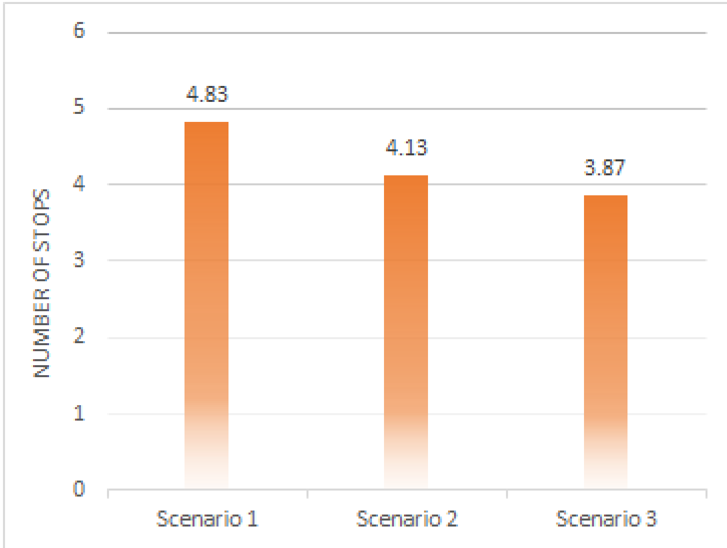

Figure 11. Average number of stops in the William Penn Highway network during PM peak

There were similar results in the Baum-Centre Corridor network showing that average number of stops under the existing timing operation was decreased by the Synchro optimized timings, and further decreased by the optimized offsets using the queue measurements. Figure 12 & 13 below show the change in average number of stops in the Baum-Centre Corridor network under the three different signal operations during peak hours.

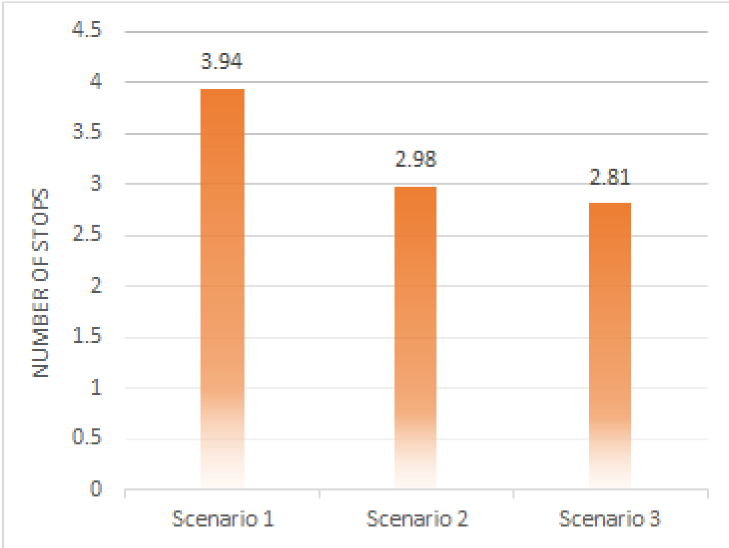

Figure 12. Average number of stops in the Baum-Centre Corridor network during AM peak

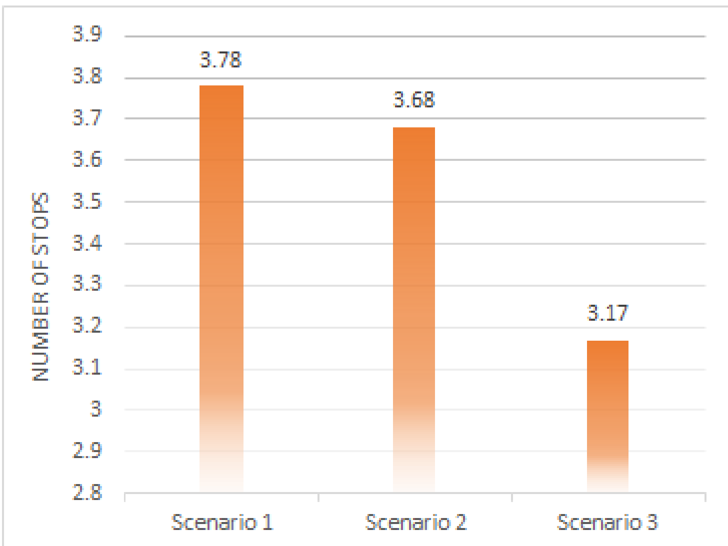

Figure 13. Average number of stops in the Baum-Centre Corridor network during PM peak

4.3.1.2 LOS of intersections

The researchers measured the changes in LOS of each intersection between the three different signal operations in the peak hours. For the William Penn Highway network, these changes in

LOS are shown in Figure 14 & 15. For the purpose of the below figures scenarios 1, 2 and 3 are referred to as existing (Ext.), optimized (Opt.) and Queue information (Qinfo.).

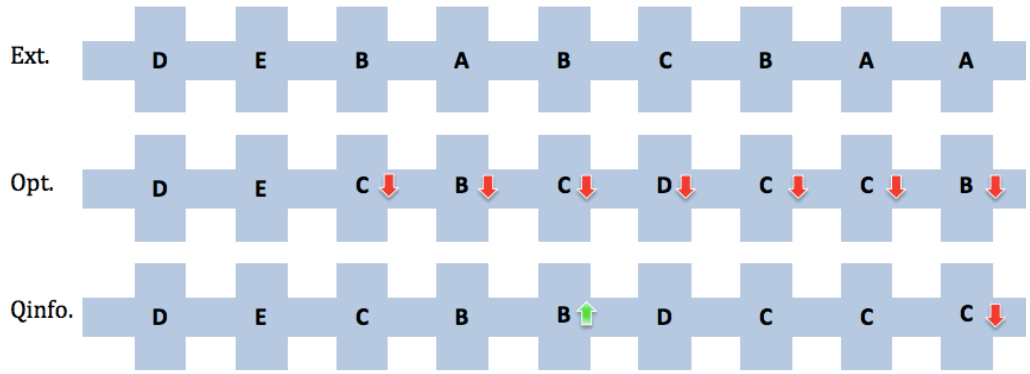

Figure 14. LOS of intersections along William Penn Highway in the AM peak

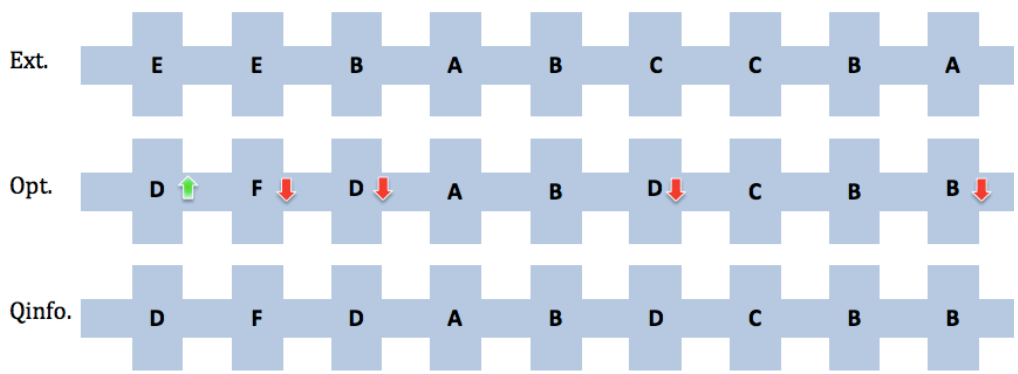

Figure 15. LOS of intersections along William Penn Highway in the PM peak

From the two figures, it can be seen that the Synchro optimal timing operation decreased LOS of many intersections in the VISSIM simulation. The possible reason is that Synchro assigned more green time on the major road in retiming, which caused more delay on minor streets. Improved signal coordination using queue length information did not improve LOS much, probably because reductions in delay at signals were not sufficiently large to change the LOS based on the delay range.

Figure 16 & 17 below show LOS of intersections during the peak hours in the Baum-Centre Corridor network. The optimized signal timings were operating well at intersections along Baum Boulevard during the PM peak. But at the AM peak LOSs of three intersections along Centre Avenue were degraded. Improved offsets using the queuing information provided some intersections with better LOS but cause additional delays at some other signals.

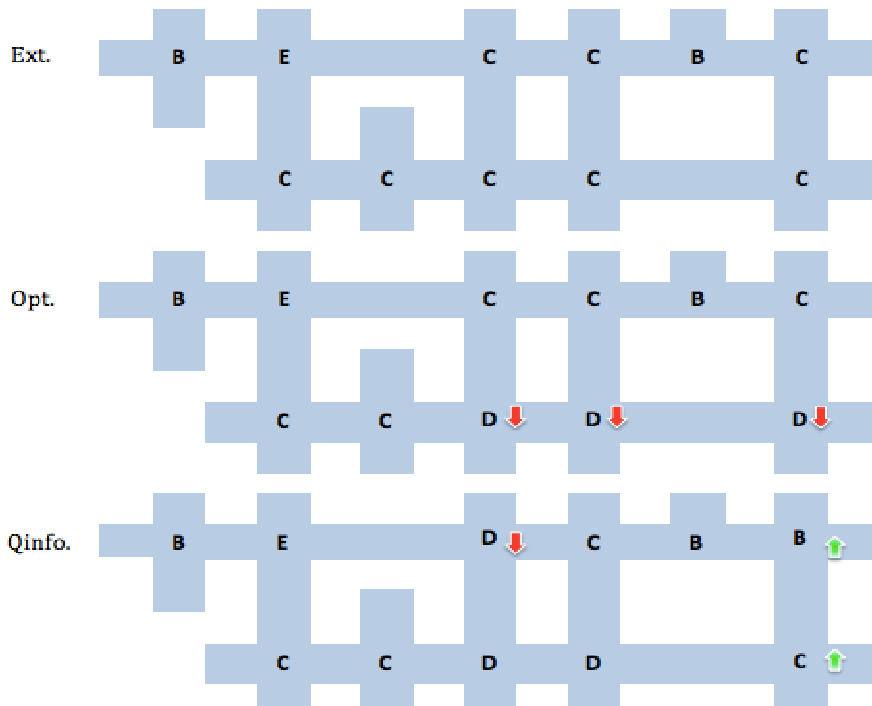

Figure 16. LOS of intersections along Baum-Centre Corridor in the AM peak

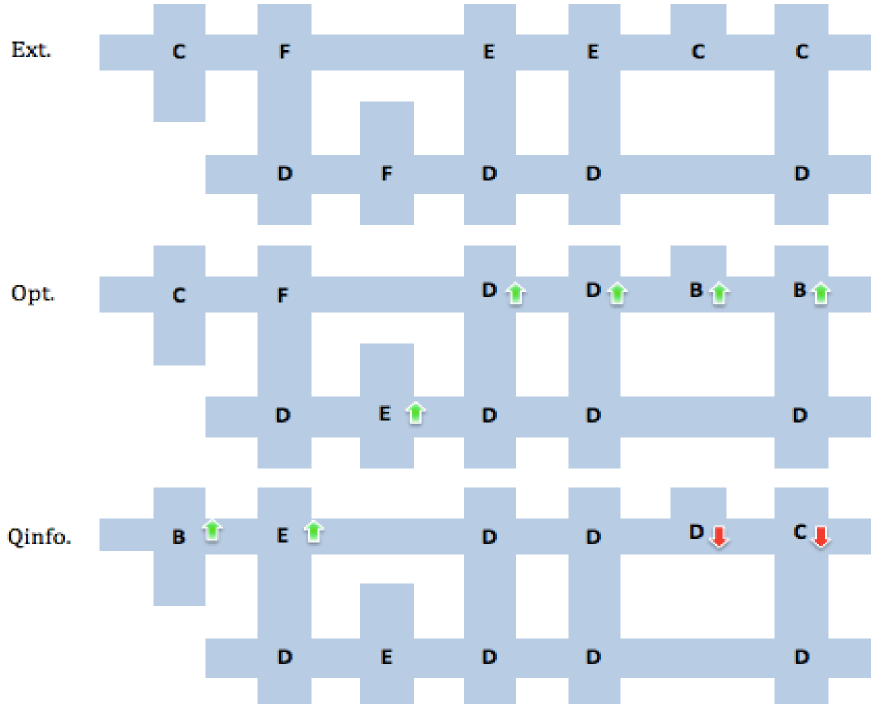

Figure 17. LOS of intersections along Baum-Centre Corridor in the PM peak

4.3.1.3 Travel time

In measuring the average travel time taken to pass through a coordinated corridor, an eastbound route and a westbound route along the main road were specifically defined in VISSIM. Figures 18 & 19 show the comparison of average travel time to finish the routes along William Penn Highway between under the three different signal operations during the peak hours.

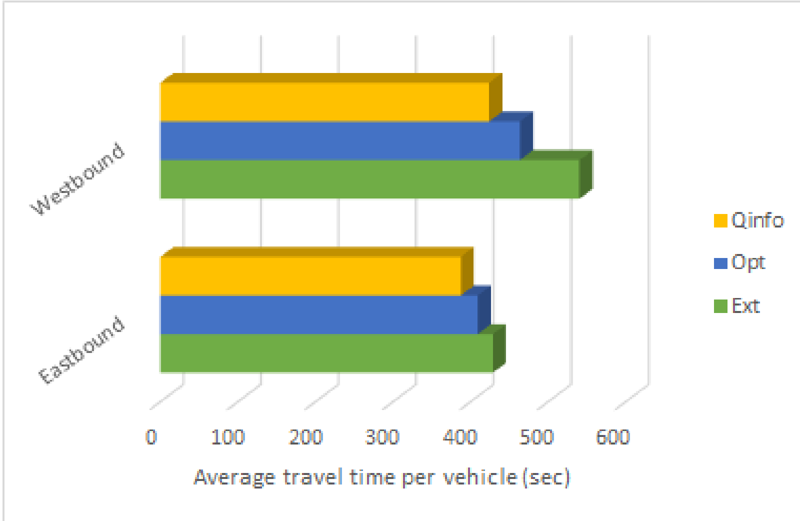

Figure 18. Average travel time for the two identified routes along William Penn Hwy in AM peak

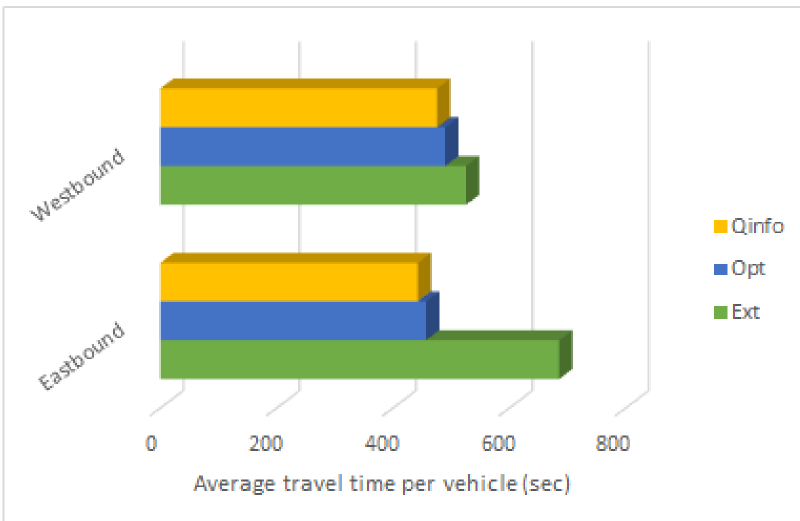

Figure 19. Average travel time for the two identified routes along William Penn Highway in PM peak

In the AM peak hour vehicles traveling towards west, which was the predominant direction of traffic flow. The Synchro retiming operation helped these vehicles save more than one minute on the average travel time to finish the route. The average travel time was further reduced by efficiently adjusting timing offsets based on the queue measurements and 8.6 percent of average travel time was saved compared with the vehicles under the Synchro retiming operation. Although traffic flows on the westbound approach were preferred in determining timing offsets, average travel time from west to east was also reduced with the Synchro optimized timings, and reduced by 5.3 percent with the optimal timing offsets when compared to with the Synchro optimized timings.

In the PM peak hour the primary traffic direction was eastbound. It took about 11.4 minutes for a vehicle to finish the route under the existing timing operation. After retiming it only took 7.6 or 7.4 minutes under the two other signal operations. The use of the developed timing offsets improved the travel time under the Synchro optimized operation by 2.9 percent. Meantime the average travel time in the west direction was improved as well. The use of the developed timing offsets improved the travel time under the Synchro optimized operation by 3.1 percent.

For the Baum-Centre Corridor network, however, the benefit of less travel time was not notable in the city street network. As shown in Figures 20 and 21, average travel time under the optimized signal operation, or under the operation with improved offsets, was not always less than that under the existing timing operation. The researchers explored the timing plans at signals and found that on the major approaches less green time was assigned for left-turn protected phases at many intersections in the Synchro timing optimization. In the test section of Baum Boulevard and Centre Avenue there is no left or right turn lane on the eastbound and westbound approaches. Conflicts with turning vehicles on shared lanes might delay the through movement of vehicles recorded in the travel time simulation. The timing offsets developed using the queue measurements may not provide a good progression where time for the queue clearance is unpredictable due to a lack of auxiliary turn lanes.

It can be seen from Figure 21 that under the operation with developed offsets, travel time was reduced in one direction of flow but increased in the opposite direction, compared with that under the Synchro optimized signal operation. This is because traffic flows in the peak direction were more predominant in adjusting timing offsets at signals. Also the Baum-Centre corridor is located in an urban area where bidirectional traffic demands are commonly present and therefore improving travel times is more difficult using offsets. Compared with William Penn Highway serving movements into and out of Pittsburgh, the city street corridor does not have as strong directional distributions.

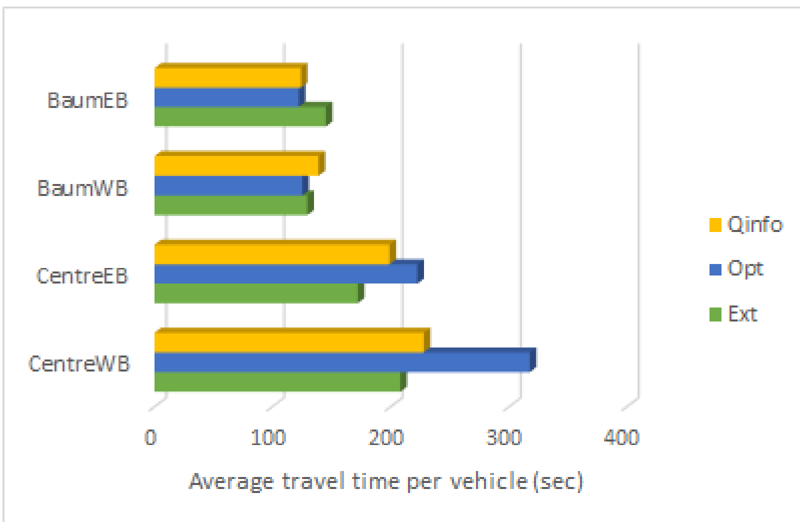

Figure 20. Average travel time for the four identified routes along Baum-Centre Corridor in AM peak

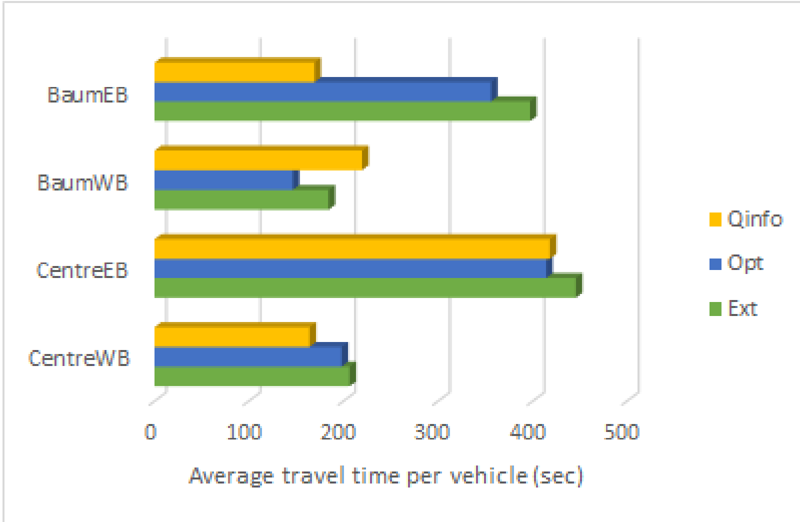

Figure 21. Average travel time for the four identified routes along Baum-Centre Corridor in PM peak

4.3.2 Efficiency in Off-peak Hours

The signal operation using the queuing information did not work well during the off-peak hours. By comparing network performance and average travel time in the two networks, no data indicated that the signal operation improved using the queuing measurements when compared to the signal operation improved by Synchro. The reason is that traffic volumes on all approaches were more balanced in the off-peak hour than the peak hour. A sample intersection of William Penn Highway was analyzed below to clarify the explanation. Figure 22 and 23 show the time-space diagrams of the William Penn Highway and Branthoover Cutoff intersection during the peak and off-peak hours respectively.

From the time-space diagram in Figure 22, it can be noted that bandwidth in the peak hour was so large that timing offset could accommodate traffic flows in the west direction, and to a great extent accommodate traffic flows in the opposite direction. While in the off-peak hour traffic directional split in the east-west direction was largely decreased at the adjacent intersection, due to the balanced traffic volumes. As a result, the bandwidth became slim and a large number of vehicle paths were blocked. In such a case it was difficult to adjust timing offsets to accommodate traffic flows in both directions at the same time. Sometimes the timing offsets developed using the queuing information may cause more delays if there is no strong directional distribution along the corridor, compared with the Synchro optimized timing operation. Therefore, benefits from the use of queue measurements were very limited during off-peak hours.

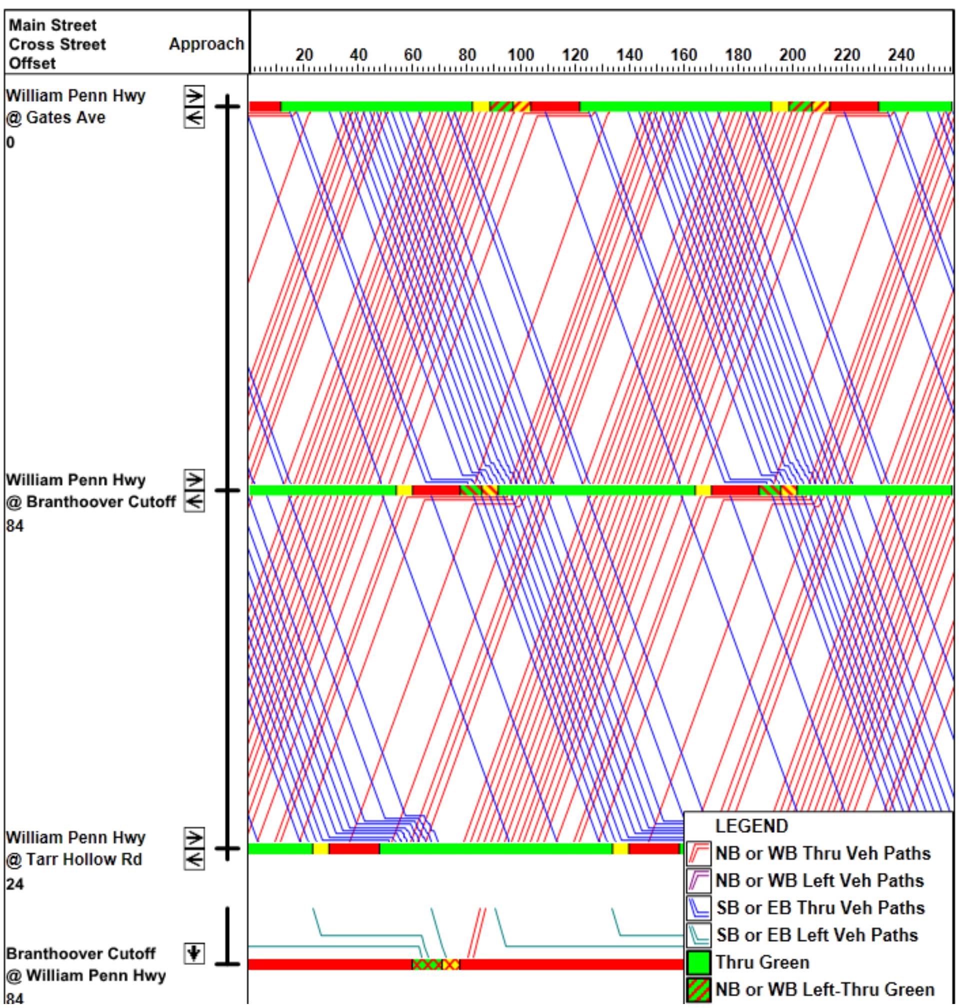

Figure 22. Time-space diagram of int. of William Penn Hwy & Branthoover Cutoff in the AM peak hour

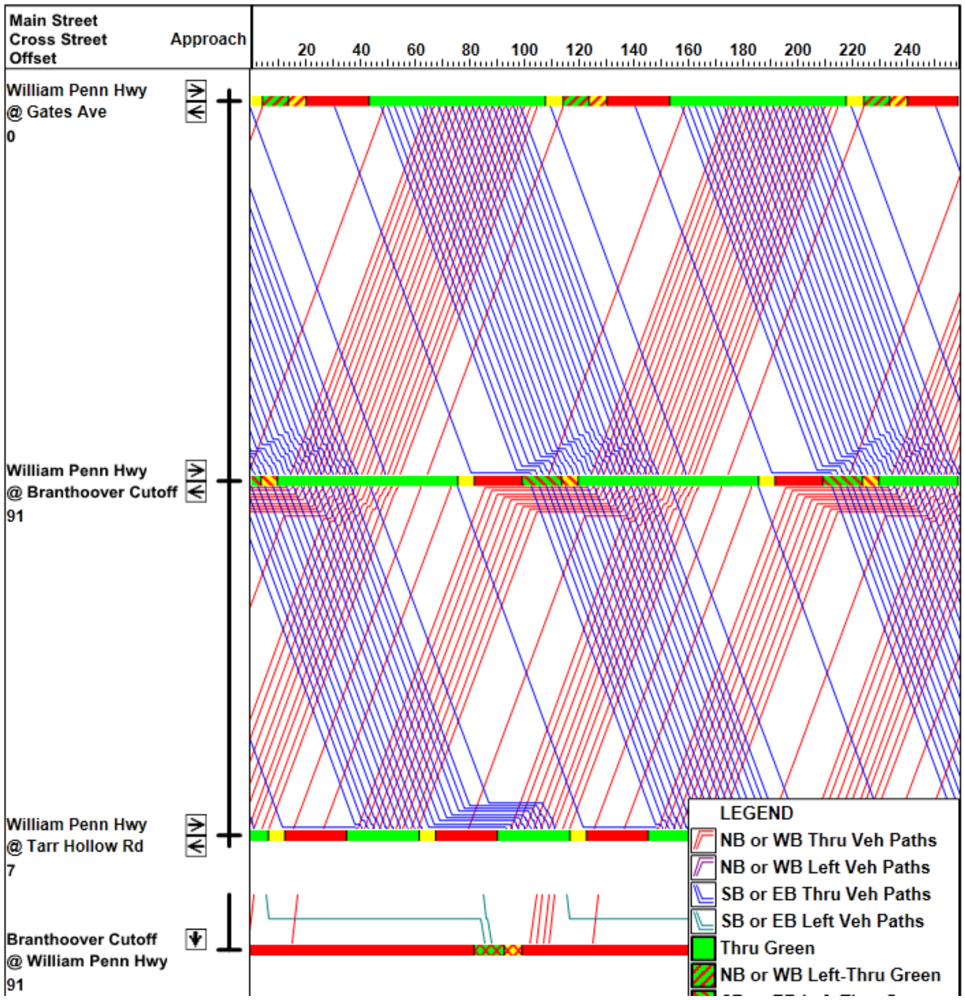

Figure 23. Time-space diagram of int. of William Penn Hwy & Branthoover Cutoff in the MD hour

4.3.2.1 Network performance

Figure 24 presents that the Synchro optimized timing operation efficiently reduced average delay per vehicle by 11.75% in the William Penn Highway when compared to the existing timing operation. The developed timing offsets using the queue measurements did not further reduced but cause additional delays for each vehicle on average during the off-peak hour. Compared with under the existing operation, the average delay per vehicle was less efficiently reduced by 5.8% under the signal operation with Synchro timings and developed offsets. While in the Baum-Centre Corridor network (shown in Figure 25), the developed offsets using the queuing information caused the most delays for vehicle for the network during the off-peak hour.

Figure 24. Average delay per vehicle in the William Penn Highway network during MD hour

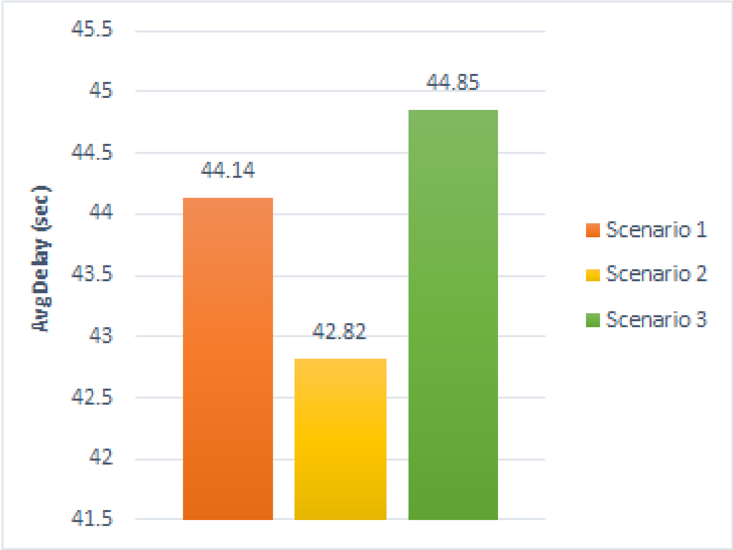

Figure 25. Average delay per vehicle in the Baum-Centre Corridor network during MD hour

In Figure 26, average number of stops was largely decreased after retiming by Synchro but slightly increased when the developed offsets were used in the Mid-day hour. It can be seen from Figure 27, the number of stops was the least under the existing timing operation. Whereas the most number of stops occurred when adopting the timing offsets developed using the queue measurements.

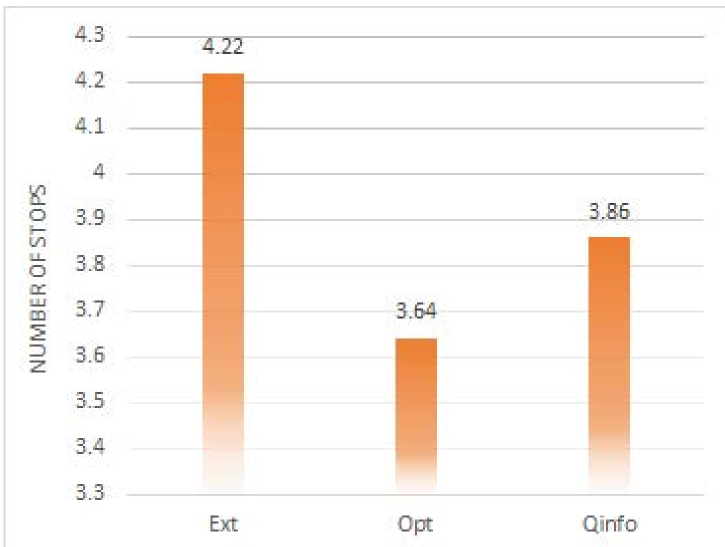

Figure 26. Average number of stops in the William Penn Highway network during MD hour

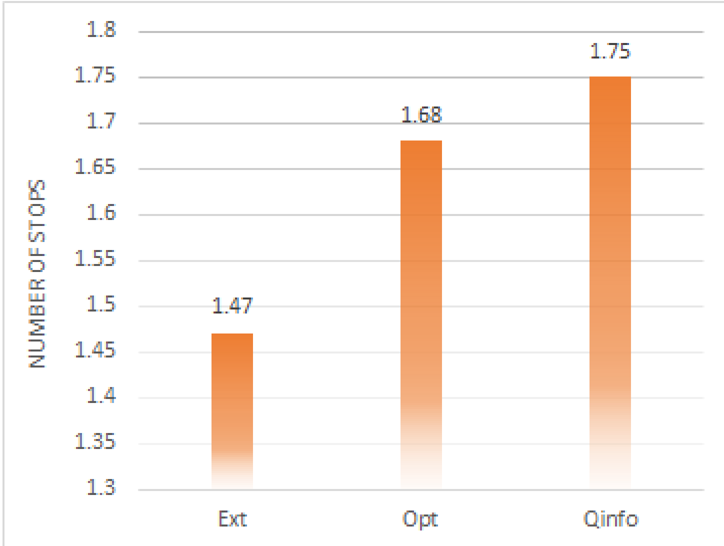

Figure 27. Average number of stops in the Baum-Centre Corridor network during MD hour

4.3.2.2 LOS of intersections

Along William Penn Highway and Baum-Centre Corridor, LOS of many intersections was improved or worsened after Synchro retiming. Figure 28 and 29 exhibits the changes in LOS at intersections among the three different signal operations in the Mid-day hour, respectively for the two test networks. It was same with during the peak hours, using the developed timing offsets did not significantly change LOS at intersections in the off-peak hour. Because the proposed method is adjusting timing offsets to improved signal coordination along a corridor, which may not necessarily reduce the control delay much at a node.

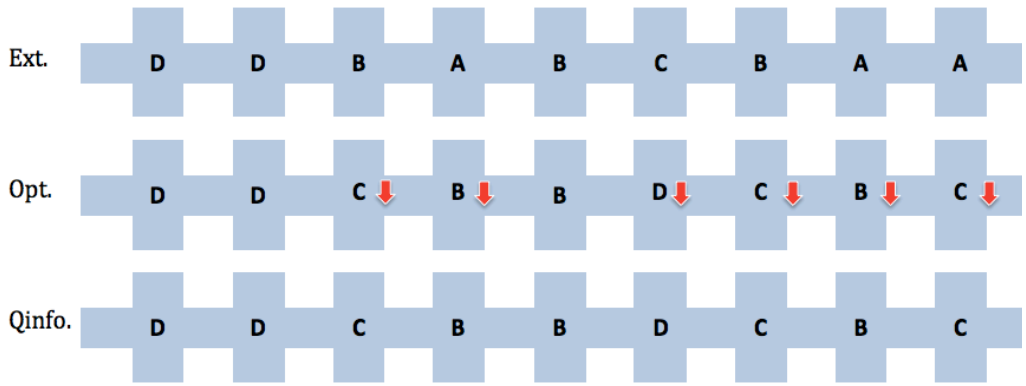

Figure 28. LOS of intersections along William Penn Highway in the MD hour

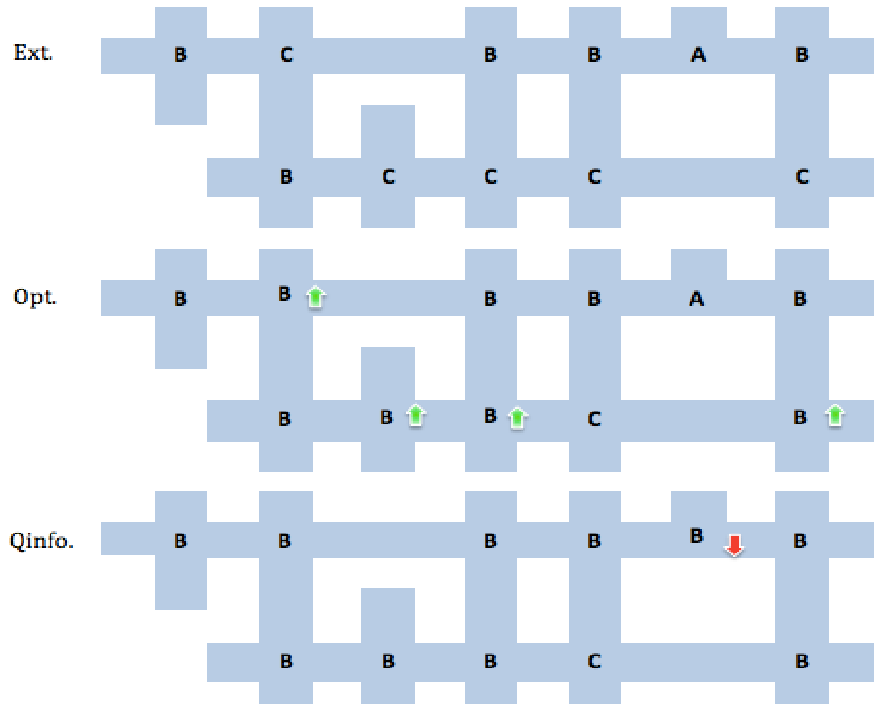

Figure 29. LOS of intersections along Baum-Centre Corridor in the MD hour

4.3.2.3 Travel time

Because of the balanced traffic volumes, the signal operation with the developed timing offsets did not provide a good progression during the off-peak hour in the two test corridor networks. According to Figure 30 and 31, the signal operation improved using queue information saved little travel time in the two test corridor networks when compared to the Synchro optimized timing operation.

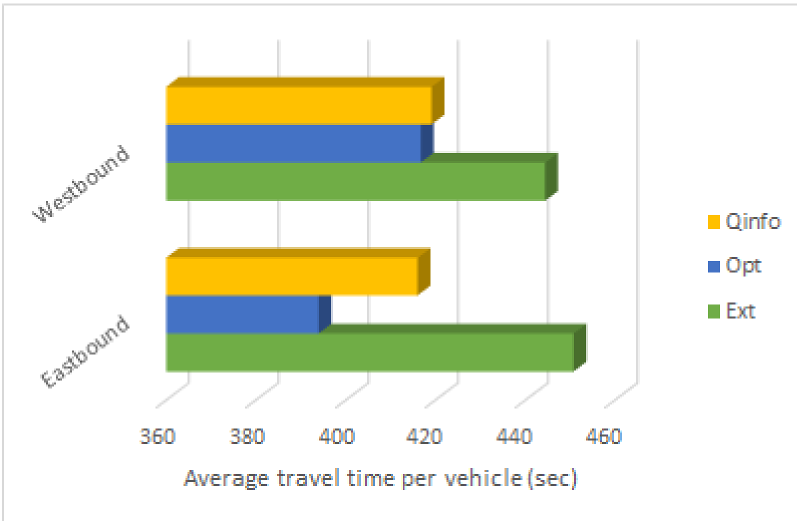

Figure 30. Average travel time for the two identified routes along William Penn Hwy in MD hour

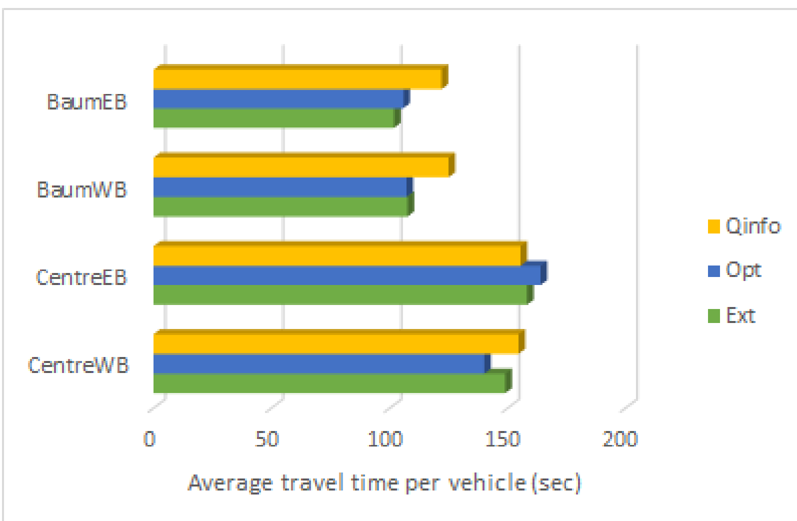

Figure 31. Average travel time for the two identified routes along Baum-Centre Corridor in MD hour

4.4 REQUIRED CV MARKET PENETRATION RATE

The researchers investigated the minimum market penetration rate required to realize the benefits of CV data, which can provide useful information to the test and deployment of the CV technology. Because the use of queuing information significantly benefited the network performance during the peak hours, average delay and average number of stops per vehicle in the AM and PM peaks were considered as the measures in determining the required penetration rate. The values of average delay and stops under the Synchro optimized timing operation were considered as the baselines for measuring progress in signal operation using CV information. The researchers developed timing offsets, based on the boundary values of queue length estimation under different penetration rates, and input them into VISSIM to run simulations. Test values out of VISSIM were presented in Table 23 for the William Penn Highway network and Table 24 for the Baum-Centre Corridor network. A red highlight indicates that the value is beyond the corresponding baseline and no benefit was achieved in the case.

Table 23. William Penn Highway network performance under different CV market penetration rates

Penetration Rate	AM peak		PM peak	
	DelayAvg/vehicle (sec)	StopsAvg/vehicle	DelayAvg/vehicle (sec)	StopsAvg/vehicle
Baseline	**79.52**	**4.02**	**132.83**	**4.13**
100%	72.2	3.73	124.72	3.87
90%	78.1	3.82	134.15	4.01
	75.94	3.75	137.97	4.09
80%	76.59	3.94	131.97	4.1
	79.06	3.7	129.54	4.09
70%	74.89	3.69	130.4	3.85
	74.38	3.58	129.12	3.96
60%	75.54	3.96	132.41	4.01
	78.02	3.83	131.16	3.92
50%	73.45	3.66	136.86	4.35
	72.75	3.52	135.65	4.07
40%	79.84	3.76	135.45	4.06
	80.39	3.7	133.02	3.86
30%	78.29	3.75	134.79	4.11
	78.1	3.86	133.06	3.95
20%	77.69	3.76	131.53	3.85
	81.6	3.92	134.15	4.05
10%	74.33	3.51	138.89	4.16
	81.12	4.07	130.04	4.05

Table 23 displays that the network performance was not improved when the CV penetration rate was low in the traffic stream. There is no predicted relationship between network performance and penetration rate because, based on the equation, other factors may affect the network performance. The data can only reflect a basic trend of efficiency of the proposed method, which is under a penetration rate of more than 60% the timing offsets developed using the queue length information probably improve the Synchro optimized timings operation. It is also noted this comparison is based upon three simulation runs. Additional runs could provide more information about the relationship.

Table 24. Baum-Centre corridor network performance under different CV market penetration rates

Penetration Rate	AM peak		PM peak	
	DelayAvg/vehicle (sec)	StopsAvg/vehicle	DelayAvg/vehicle (sec)	StopsAvg/vehicle
Baseline	**109.29**	**2.98**	**145.3**	**3.68**
100%	94.61	2.81	113.87	3.17
90%	100.45	2.91	120.02	3.32
	93.25	2.65	124.02	3.38
80%	96.36	2.96	120.27	3.28
	93.92	2.72	137.16	3.4
70%	97.5	2.8	119.81	3.23
	98.54	2.86	119.24	3.23
60%	100.36	2.94	121.67	3.25
	109.41	3.01	120.2	3.26
50%	91.49	2.8	125.04	3.42
	94.07	2.7	113.56	3.19
40%	98.27	2.95	124.15	3.44
	98.29	2.84	122.53	3.23
30%	97.99	2.76	124.19	3.42
	96.47	2.85	114.94	3.2
20%	93.26	2.57	141.12	4.02
	96.72	2.74	117.61	3.19
10%	100.75	2.85	132.17	3.6
	97.59	2.72	117.96	3.11

According to the data shown in Table 24 the performance of the Baum-Centre Corridor network was improved using the queue length information, even though the queue length estimation might not be precise. It can be explained that under the saturated traffic condition vehicle queues might not be cleaned within a signal cycle and the effect of queues on the signal coordination might become negligible. In such cases the time used to travel from an upstream intersection to a downstream intersection is much more than the time used for the queue clearance at the downstream intersection, the formula used in the proposed approach has to be adjusted. Measuring accurate platoon speed information using the CV technology important for coordinated traffic signal systems such as these. Because even at a 10% penetration rate the sample size is large enough on a road with heavy traffic and it is simple to collect speed data from connected vehicles instead of queue information, it may be possible to improve signal operation in the corridor network under a 10% penetration rate using speed information rather than queue information.

Using CV speed information instead of queue information to recalculate offsets in an urban environment cannot be tested in a simulation. This is because speeds do not vary based on inaccurate queue information from CVs, they are only based on actual queues.

5.0 SUMMARY AND CONCLUSIONS

The chapter summaries the research procedure and test results and provides conclusions for the use of CV data in coordinated traffic signal systems.

5.1 SUMMARY OF RESULTS

The purpose of this research was to determine if traffic mobility in corridor networks could be improved by determining timing offsets at coordinated signals based on queue length information available from connected vehicles. The benefits of this V2I application were measured using network performance, LOS of intersections and travel time in an urban street corridor network and a suburban highway corridor network using the simulation program VISSIM. In addition, minimum CV penetration rate required for the application in the two test networks has been identified by simulation tests.

5.1.1 Network performance

Compared with Synchro optimized timing operation, the developed timing offsets helped reduce average delay by 9.2% and 6.1% during the AM and PM peak in the suburban highway corridor network, and by 13.4% and 21.6% during the two peak hours in the urban street corridor network.

When compared to vehicles under the Synchro optimized timing operation, the average number of stops of vehicles under the operation with the optimal offsets decreased by 7.2% and 6.3% during the AM and PM peak in the suburban highway corridor network, and by 5.7% and 13.9% during the two peak hours in the urban street corridor network.

In the Mid-day hour network performance including average delay and stops per vehicle was not improved in both the two test corridor networks due to balanced traffic volumes.

5.1.2 LOS of Intersections

Although using the developed timing offsets reduced more delays than the Synchro optimized timing offsets for the complete test networks, control delay and LOS at intersections were not significantly decreased in simulations.

5.1.3 Travel Time

The average travel time was decreased by adjusting timing offsets based on the queue measurements during the peak hours in the suburban highway corridor network. The decreases in travel time were up to 8.6 percent when compared to travel time under the Synchro optimized operation. But for the urban street corridor network, travel time was not efficiently saved by adjusting timing offsets during the peak hours because of the bidirectional traffic demands and the lack of alleyway lanes.

With the balanced traffic volumes, the signal operation with the developed timing offsets did not provide a good progression during the off-peak hour in the two test corridor networks.

5.2 CONCLUSIONS

It was concluded that incorporating queue length information available from connected vehicles into the optimization of signal offsets can improve coordinated traffic signal systems on corridors. Compared to the current signal retiming approach, the Vehicle-to-Infrastructure (V2I) application helped vehicles reduce up to 21.6 percent delay and 13.9 stops in the test corridor networks during the traffic peak hours.

According to the test results, the V2I application worked better in the test urban street corridor network than the test suburban highway corridor network. Although travelers experienced less travel time at the corridor level in the suburban highway corridor network, signal operation in the urban street corridor network provided travelers with a better optimized signal timing coordination and less delay in the complete corridor network.

Based on multiple runs of simulation under different connected vehicle market penetration rates, the use of the queue measurements could bring benefits to the test urban street corridor network when speed information instead of queue information was used from 10% connected vehicles in the traffic stream. While at least 60% penetration rate is required for the implementation of the V2I application in the test suburban highway corridor network for queue information.

5.3 RECOMMENDATIONS FOR FUTURE RESEARCH

In the research the queue measurements were used to optimize timing offsets for the TOD signal timing plans. It is the same with traffic volumes, queue lengths at an intersection varies every cycle. If the timing offsets are frequently adjusted based on the cycle-to-cycle queue size, the efficiency of the coordinated signal timing systems would be largely improved. The future research can explore if it is possible to develop timing offsets for the adaptive signal control systems using queue length information available from connected vehicles under a relatively low market penetration rate.

APPENDIX A

OPTIMIZATION OF TIMING OFFSET USING QUEUING INFORMATION

The section lists data output from SimTraffic and calculations of timing offsets.

A.1 AVERAGE QUEUE & PLATOON SPEED

Table 25. Average queue length and platoon speed for intersections along William Penn Hwy

Node #.		1	2	3	4	5	6	7	8	9
Distance (ft)		1783	1330	2937	2740	1950	1649	2462	1442	5509
AM Peak	Avg Speed (mph)	22	15.5	34.5	34	31.5	27.5	29.5	33	40
		23	16.5	35	34	31	25.5	29.5	33	40.5
		23	15	35	35.5	32	27	29.5	33	40.5
		22.5	15	35	35	32	29.5	29	32	41
		23	16.5	35	35	33	28.5	30	33	40.5
	Avg Queue (ft)	225	342	57	80	64	131	144	32	39
		200	292	39	72	62	176	118	49	10
		233	321	52	57	50	138	144	39	25
		303	346	38	60	63	94	145	47	30
		207	305	44	65	37	114	114	37	26
MD Peak	Avg Speed (mph)	23	29.5	36	33.5	21	29.5	33.5	38	40
		21	29	36	33.5	20.5	29.5	34	38.5	39.5
		20.5	29	35.5	34	20.5	28.5	33.5	38	39.5
		22.5	30	36	33.5	19.5	29.5	33	37	39
		20	29.5	36	32.5	19.5	28	34.5	39.5	39.5
	Avg Queue (ft)	194	46	30	101	217	83	78	10	64
		236	53	35	95	228	102	80	11	89
		237	50	27	83	219	102	76	14	75
		178	41	17	112	249	81	90	13	75
		272	29	24	119	246	117	55	5	88
PM Peak	Avg Speed (mph)	17	27	35	30.5	17.5	27.5	31.5	36.5	37.5
		14	28	35	31.5	18	29.5	32.5	37	38.5
		16	28.5	35	31.5	17.5	28.5	30.5	36.5	37
		17	28	35.5	32	18	27	30.5	37	37
		17	29	34.5	31	18	29	31.5	36.5	37
	Avg Queue (ft)	395	24	21	181	389	127	144	26	132
		601	25	27	152	338	82	123	26	107
		417	8	42	172	393	90	170	14	137
		382	24	21	150	352	127	153	12	146
		347	12	34	182	375	87	147	13	149

Table 26. Average queue length and platoon speed for intersections along Baum-Centre corridor

Node #.		100	105	110	115	116	120	205	210	215	220	225
Distance (ft)		397	1187	717	548	426	691	352	690	873	877	878
AM Peak	Avg Speed (mph)	16.5	21.5	13	11	21	18.5	9	14	16	15	17
		17	21	12	7	9	8.5	10	15	15	7	16
		16.5	21	13.5	12	22.5	18.5	9	14	16	10	17
		16	20	12.5	9.5	23	19	7	12	16	13	16
		16.5	20	13.5	11	18	19	10	14	16	12	16
	Avg Queue (ft)	49.5	63	140	191.5	26	87	119	147	120	132	148
		43	91.5	160.5	291	116	210.5	125	142	115	335	168
		49	74	122.5	133	18.5	65.5	133	148	98	210	117
		54.5	98	163	183	16.5	77.5	144	169	114	177	147
		61	102.5	141	199	39	73	111	148	106	154	156
MD Peak	Avg Speed (mph)	14.5	23	13	21	14.5	14	10	16	16	17	11
		15	23.5	13.5	20.5	15.5	14	10	16	15	17	12
		14.5	23.5	14	19.5	14	14	10	16	15	16	10
		14	22	13.5	20	14.5	14	10	17	15	18	11
		14.5	23	13.5	21	14.5	14.5	11	17	16	17	11
	Avg Queue (ft)	39.5	48	121	29.5	55.5	93	113	80	103	108	178
		28.5	47	106.5	34.5	44	88	109	61	105	96	170
		30.5	52.5	107.5	44.5	57.5	107	114	81	118	99	248
		38.5	58	116.5	36.5	57	90	95	79	110	70	172
		35.5	52	115.5	34	50	89.5	90	59	99	77	195
PM Peak	Avg Speed (mph)	11	6.5	5	5.5	4	3.5	5	5	4	4	6
		11.5	6	4	4.5	4.5	4	7	8	11	5	5
		16	10.5	6	6.5	5	4	4	5	5	4	5
		16	11	4	5.5	4.5	3.5	7	7	7	4	6
		16	16.5	12	17	8	4	9	11	16	10	5
	Avg Queue (ft)	79.5	458	403	302	300.5	541	249	428	449	541	381
		82	532.5	515	392	310.5	554	239	368	243	517	518
		46.5	288.5	341.5	252	277.5	568.5	259	419	432	541	461
		53	308	530.5	324.5	309	571	196	286	309	480	400
		49.5	213.5	236.5	97.5	212.5	522.5	183	243	134	250	580

A.2 OPTIMAL TIMING OFFSET

The optimal offsets were determined by the equation below.

$$offset\ (s) = \frac{D}{S} - (Nh + \ell_1)$$

Where $h = 1.9s/veh, \ell_1 = 2\ s, N = \frac{Q}{20\ ft/veh}$ and D, S, Q are given.

Table 27. Optimal timing offsets for intersections along William Penn Hwy

Node #.		1	2	3	4	5	6	7	8	9
Distance (ft)		1783	1330	2937	2740	1950	1649	2462	1442	5509
AM Peak	Avg Speed (mph)	22.7	15.7	34.9	34.7	31.9	27.6	29.5	32.8	40.5
	Avg Queue (ft)	233.6	321.2	46	66.8	55.2	130.6	133	40.8	26
	Offset (sec)	29.24	25.11	50.88	45.37	34.34	26.24	42.1	24.03	88.1
	Syn. Offset (sec)	59	40	0	84	24	3	68	109	56
MD Peak	Avg Speed (mph)	21.4	29.4	35.9	33.4	20.2	29	33.7	38.2	39.5
	Avg Queue (ft)	223.4	43.8	26.6	102	231.8	97	75.8	10.6	78.2
	Offset (sec)	33.46	24.61	51.13	44.12	41.65	27.47	40.5	22.67	85.4
	Syn. Offset (sec)	52	49	0	91	7	97	99	3	64
PM Peak	Avg Speed (mph)	16.2	28.1	35	31.3	17.8	28.3	31.3	36.7	37.4
	Avg Queue (ft)	428.4	18.6	29	167.4	369.4	102.6	147	18.2	134
	Offset (sec)	32.17	28.43	52.33	41.65	37.43	27.89	37.5	23.00	85.4
	Syn. Offset (sec)	61	78	0	0	49	82	84	46	13

Table 28. Optimal timing offsets for intersections along Baum-Centre corridor

Node #.		100	105	110	115	116	120	205	210	215	220	225
Distance (ft)		397	1187	717	548	426	691	352	690	873	877	878
AM Peak	Avg Speed (mph)	17	21	13	10	19	17	9	14	16	11	16
	Avg Queue (ft)	51	86	145	200	43	103	126	151	111	202	147
	Offset (sec)	9	29	22	16	9	16	13	18	25	31	20
	Syn. Offset (sec)	0	89	40	24	9	5	39	40	84	77	43
MD Peak	Avg Speed (mph)	15	23	14	20	15	14	10	16	15	17	11
	Avg Queue (ft)	35	52	113	36	53	94	104	72	107	90	193
	Offset (sec)	13	28	23	13	13	22	12	20	26	25	34
	Syn. Offset (sec)	34	33	63	76	88	39	10	4	32	48	51
PM Peak	Avg Speed (mph)	14	10	6	8	5	4	6	7	9	5	5
	Avg Queue (ft)	62	360	405	274	282	551	225	349	313	466	468
	Offset (sec)	11	44	38	20	27	69	14	30	37	64	64
	Syn. Offset (sec)	19	34	84	91	8	20	73	79	82	88	71

BIBLIOGRAPHY

Yiheng Feng and et al, "A Real-time Adaptive Signal Control in a Connected Vehicle Environment," *Transportation Research Part C*, Volume 55, June 2015, Pages 460-473.

Federal Highway Administration, “Identification of State and local Policy and Planning Actions that Could Facilitate Implementation of CV and AV Systems,” 2015.

United States Department of Transportation, “Connected Vehicle Research in the United States,” 2015.

Kevin Balke, Hassan Charara and Srinlvasa Sunkari, "Report on Dynamic Speed Harmonization and Queue Warning Algorithm," FHWA-JPO-14-168, United States Department of Transportation, January 2014.

Louisiana Transportation Research Center, “Development of a Simulation Test Bed for Connected Vehicles using the LSU Driving Simulator,” 2015.

Texas Department of Transportation, “Connected Vehicle Problems, Challenges, and Major Technologies,” 2015.

Federal Highway Administration, “Vehicle to Infrastructure Deployment Guidance and Products,” 2015.

Washington State Department of Transportation, “Connected Vehicles and Smart Cities,” 2015.

Florida Department of Transportation, “Utilization of Connected Vehicle Data to Support Traffic Management Decisions,” 2015.

Florida Department of Transportation, “Development and Testing of Optimized Autonomous and Connected Vehicle Trajectories at Signalized Intersections,” 2015.

Alex Skabardonis, "Advanced Traffic Signal Control Algorithms," CA13-2157-A, California Department of Transportation, September 2013.

Joyoung Lee, Byungkyu Park and Ilsoo Yun, "Cumulative Travel-Time Responsive Real-time Intersection Control Algorithm in the Connected Vehicle Environment," *Journal of Transportation Engineering*, Volume 139, Issue 10, October 2013.

S.Ilgin Guler, Monica Menendez, and Linus Meier, "Using Connected Vehicle technology to Improve the Efficiency of Intersections," *Transportation Research Part C*, Volume 46, September 2014, Pages 121-131.

Jing-Quan Li, Kun Zhou, Steven E. Shladover, and Alexander Skabardonis, “Estimating Queue length Under Connected Vehicle Technology: Using Probe Vehicle, Loop Detector, and Fused Data”, *Transportation Research Record*, 2013.

Roger Roess, Elena Prassas and William McShane, *Traffic Engineering (Fourth Edition)*, 2011, Chapter 26, p649.

Trafficware, *Synchro Studio 8 User Guide*, 2014, Chapter 13.