DETERMINING THE ENVIRONMENTAL BENEFITS OF ADAPTIVE SIGNAL CONTROL SYSTEMS USING SIMULATION MODELS

by

Xin Wei

B.S Engineering, Nanjing Agriculture University, 2013

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SWANSON SCHOOL OF ENGINEERING

This thesis was presented

by

Xin Wei

It was defended on

March 20, 2015

and approved by

Mark Magalotti Ph.D. P.E., Senior Lecturer, Department of Civil and Environmental Engineering

Leonard Casson, PhD. P.E., Associate Professor, Department of Civil and Environmental Engineering

Steve Stuart P.E. PTOE

Thesis Advisor: Mark Magalotti Ph.D. P.E, Senior Lecturer, Department of Civil and Environmental Engineering

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Adaptive Traffic Control Systems (ATCS) have recently been implemented across the world and are considered as a new tool to reduce traffic delays and stops in coordinated traffic signal systems, which are urgent problems regarding not only traffic flow efficiency, but also environmental issues. Excessive fuel consumption and vehicular emissions on urban streets can be reduced by maintaining optimal signal timings which reflect changes in traffic demand and distribution. It is hypothesized that there are environmental benefits to implementing ATCS as compared to traditional Time of Day (TOD) plans. This research develops a methodology to quantify these benefits and tests the methodology to establish the reduction in emissions for a signalized roadway corridor as a line source of emissions. The research also considers the linking between microsimulation models, emission models and dispersion models to estimate air quality benefits in a corridor at specific receptors.

This testing of the methodology was conducted by using a high-fidelity SYNCHRO microsimulation model of an 8-intersection corridor on Route 19 in Pittsburgh Pennsylvania. This signal system was recently converted from a traditional TOD timing plan operation to an ATCS operation, using the InSync system. The simulation results comparison showed significant reductions in all emission categories estimated by SYNCHRO. Using simulation results from SimTraffic for an optimized TOD timing plan and the InSync system actual operations, a methodology was then hypothesized to integrate simulation emission results of the ATCS benefits with emission and dispersion models to indicate emission benefits at specific receptors.

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PREFACE

This thesis is made as a completion of the master education in Transportation Engineering. Yours truly has a bachelor degree in Traffic and Transportation Engineering from Nanjing Agriculture University and this thesis is the product of the master period, which is the conclusion part of the Transportation study at University of Pittsburgh, Swanson School of Engineering, Civil and Environmental Engineering Department.

Several persons have contributed academically, practically and with support to this master's thesis. I would therefore firstly like to thank my head supervisor, Mark Magalotti. He gave me a lot of trust and flexibility on the research. Without him, I could not have such an amazing experience in such a challenging research; without him, I could not collect data so quickly and complete this research in time.

Furthermore I would like to thank James Cullison, my modelling instructor. He gave me not only a lot of detailed instructions on my modelling process but also many useful practical comments over data processing.

I would also like to thank Dan Szekeres and Steven J. Stuart from Michael Baker International, who provided the counting data and also gave a lot of constructive guidance at the beginning of this research. Moreover, Tom Cooper from Rhythm Engineering provided the InSync timing data which was most critical to this research, he was really appreciated for his assistance on my data collection.

Last but not least, I would like to thank my family and friends for being helpful and supportive during my time studying at University of Pittsburgh.

Today I finished my master’s thesis and I will continue to challenge myself in the future with what I learned. This is not the end but only the start.

1.0 INTRODUCTION

Adaptive Traffic Control Systems (ATCS) have recently been implemented across the world and are considered as a tool to reduce traffic delays and stops in coordinated traffic signal systems, which are urgent problems regarding not only traffic flow efficiency, but also environmental issues. Excessive fuel consumption and vehicular emissions on urban streets can be reduced by maintaining optimal signal timings which reflect changes in traffic demand and distribution.

It is hypothesized that there are environmental benefits to implementing ATCS as compared to traditional Time of Day (TOD) plans. This research develops a methodology to quantify these benefits and tests the methodology to establish the reduction in emissions for a signalized roadway corridor as a line source of emissions. The research also considers the linking between microsimulation models, emission models and dispersion models to estimate air quality benefits in a corridor at specific receptors.

This testing of the methodology was conducted by using a high-fidelity SYNCHRO microsimulation model of an 8-intersection corridor on Route 19 in Pittsburgh, Pennsylvania. This signal system was recently converted from a traditional TOD timing plan operation to an ATCS operation, using the InSync system. The simulation results comparison showed significant reductions in all emission categories estimated by SYNCHRO. This first step in showing the benefits in a corridor can then be used to determine actual emission reductions at specific locations. Using simulation results from SimTraffic for an optimized TOD timing plan and the InSync system actual operations, a methodology was then hypothesized to integrate simulation emission results of the ATCS benefits with emission and dispersion models to indicate emission benefits at specific receptors.

This section introduces the background, hypothesis and objectives of this research.

1.1 BACKGROUND

Today’s traffic situations in big cities are still far from being satisfactory. Traffic congestions at rush hour or at special events occur frequently and the public complains about increased total travel time. Additionally, traffic stops and delay significantly increases vehicle emissions and fuel consumption resulting in increased levels of pollution. According to the Department of Climate Change, emissions from the transport sector have risen 28 percent increase over 1990 levels in U.S., [1] and are still projected to continue to grow strongly into the future at an average annual rate of 1.6% from 2010 to 2020. The situation is particularly dramatic in the rising megacities of Asia, Middle, and South America. The Annual Average Daily Traffic (AADT), for all roadways in China, for instance, increased in 2013 by 7.3% [2] and has continued to grow fast with more and more emissions, making sound network planning and traffic signal control indispensable to reduce the growth of emissions.

Climate change has been identified by many scientists, engineers, and public officials as one of the significant challenges facing society over the next several decades. Automobile exhaust is a major source of air pollution and climate change, and also is one main contributing factor of photochemical smog. With the increase of carbon dioxide levels, climate change will be exacerbated, in addition, automobile exhaust contains hundreds of different compounds, including pollutants suspended solid particles, carbon monoxide, carbon dioxide, hydrocarbons, nitrogen oxides, lead and sulfur oxide compounds. These emissions can cause great damage to human health. Automobile exhaust emissions are dispersed at a height range 1.0 to 6.0 ft. which is the range of the body's breathing area. [3] These emissions can stimulate the human respiratory tract and the respiratory system, decrease immunity, resulting in exposed populations getting chronic bronchitis, bronchitis, and an increased incidence of dyspnea, lung function decline and a series of symptoms; exhaust benzene substance is a strong carcinogen, which will lead to lung cancer, thyroid cancer, breast cancer, etc. [3]

Traffic signals affect the traffic flow significantly, especially in urban areas. Adaptive Traffic Control Systems (ATCS) has been developed to as tools to reduce traffic delays and stops in coordinated traffic signal systems, which are urgent problems regarding not only traffic flow efficiency, but also traffic environmental issues. A well designed signal operation benefits the public by increasing network efficiency and safety. On the contrary a poor operation could cause various problems including air pollution. Excessive fuel consumption and vehicular emissions on urban streets can be reduced by maintaining optimal signal timings which reflect changes in traffic demand and distribution. And in other words, the application of Adaptive Signal System can bring tremendous benefits for the environment and resulting public health.

ATCS installation have gained significant popularity in most area of United States, the effect of those systems to improve environmental conditions needs to be analyzed and demonstrated by developing a methodology to document those changes. However, few Adaptive Traffic Control deployments have been evaluated for their environmental benefits. [4]

1.2 HYPOTHESIS

The hypothesis of this research was could microsimulation models be used to predict improvements in air quality in a corridor that has implemented ATCS and how the proposed traffic simulation model could be combined with an Emission Model and Dispersion Model to determine the environmental benefits of Adaptive Traffic Signal Control System operations at specific receptors in the corridor. The challenge of this proving this hypothesis is that microsimulation models are used primarily to establish optimum timings for installation while ATCS constantly changes timings and microsimulation models are not structured to accept these types of variations, and the linking between microsimulation models and other models.

1.3 RESEARCH OBJECTIVES

The research objectives of this study were to develop a methodology to estimate emission reduction benefits by the installation of ATCS in a corridor setting for signalized intersections. The research also has tested this methodology to use microsimulation models results of an operating ATCS system to estimate emission levels in a corridor and established guidelines for linking emission and dispersion models to estimate emission levels at specific receptors in a corridor. By comparing the emissions results using microsimulation with the conventional signal timing plans, the methodology will report the change in emissions due to the operations of ATCS in the traffic network.

2.0 LITERATURE REVIEW

2.1 INTRODUCTION

This literature review evaluated the current practice and research in this area to determine guidelines for the model selection and methodologies currently used to evaluate the environmental benefits for the application of adaptive traffic signal control system instead of TOD plans currently used in conventional traffic control systems. The literature review also evaluated any practice or research completed on linking traffic simulation model emission estimates with emission and dispersion air quality models to estimate impacts at specific receptors in a signalized corridor.

2.2 AIR QUALITY MODELS AND ENVIRONMENTAL BENEFITS

Australia's Sydney Coordinated Adaptive Traffic System (SCATS) is a comprehensive traffic management system that provides adaptive traffic control, [5] amongst other functionalities. (SCATS is used in all states of Australia, in New Zealand, and in many cities internationally). Christian et al. (2011) is a significant amount of research regarding the environmental benefits of SCATS including a running study titled 'SCATS and the Environment' (SatE), which was published by the Roads and Traffic Authority of New South Wales (RTA)

(NSW). The following steps were conducted in this work using the following process: (1) study experimental design, (2) model verification, (3) scenario calibration and (4) study validation. All of these steps focused on achieving appropriate traffic control operation. The study demonstrates the novel use of travel time estimations from vehicle electronic tag measurements. The study presented the results of the demonstrated performance of SCATS in modelled traffic and environment terms. This study also provides a novel insight for managers, operators and stakeholders of SCATS (and other sophisticated traffic control systems–generally) on the technique and results from a comprehensive study that investigates the value derived from automated traffic control.

Aleksandar et al. (2012) reviewed and evaluated the SCATS Adaptive Traffic Control System in a microsimulation environment and assessed environmental benefits that such a deployment brings. In this study a high-fidelity VISSIM microsimulation model of a 14-intersection network in Park City, Utah, was developed, calibrated, and validated. [4] Special attention was given to simulating various 5-day traffic flows observed in the field. SCATS and TOD conventional traffic control are interfaced with VISSIM and their outputs are post-processed in Comprehensive Modal Emission Model (CMEM). The study findings showed that SCATS outperforms Time-Of-Day traffic control by saving approximately 2% in terms of fuel consumption and other related vehicular emissions. These moderate benefits in environmental performance measures are accompanied by larger savings in traffic performance measures (delays and stops). An analytical formula commonly used to estimate fuel consumption by traffic simulation tools was utilized to reveal the major violator of reduced fuel consumption. The findings show that most of the savings come from a reduction in number of stops which are achieved by SCATS' superior coordination of traffic on the main arterials. However this methodology linked a microsimulation model with an emission model based upon detailed traffic characteristics such as mix of vehicle types and other data which is not readily available for most evaluations. In addition, the research was short of linking emission models between others such like dispersion models.

Papson et al. (2012) integrated Synchro with MOVES and calculated emissions at congested and uncongested intersections using a time-in-mode (TIM) methodology that combines emission factors for each activity mode (i.e., acceleration, deceleration, cruise, idle) with a calculation of the total vehicle time spent in that mode. [6] Papson demonstrated that the contribution of each activity mode to intersection emissions and suggested opportunities for control strategies with the potential to affect intersection emissions.

Dongsheng et al. (2014) evaluated the performances of two typical air quality models, i.e., California Line Source Model with Queuing and Hot Spot Calculations (CAL3QHC) and California Line Source Model version 4 (CALINE4), [7] in predictions of fine particulate matter (PM2.5) and carbon monoxide (CO) at 5-min scale of an particular intersection. Results show that CAL3QHC generally performs well for 5-min predictions of both PM2.5 and CO compared with CALINE4. Besides, both models perform better at off-peak than peak periods, which can be attributed to the fluctuation of high traffic volumes as well as the more complex mechanical turbulence induced by passing vehicles in peaks. Furthermore, performances of both models are more related to wind speed particularly when predicting CO concentrations. When wind speed is less than 1m/s, both models will have better performances. The outputs of these findings demonstrates the potential of both models to be applied to forecast the real-time trends of air pollution as well as to capture the extreme values due to varied scenarios at road intersections.

2.3 SUMMARY

In summary, there is little research relating to documenting the environmental benefits of ATCS operations either through microsimulation models or field data collection in long time period observation. This research that has been conducted has used microsimulation models that generated optimized timings using ATCS optimization models and compared those results to TOD operations, however most simulations conducted did not use actual ATCS timings that were generated in the field after installation of the system. This study attempted to simulate how an ATCS would generate timings but not use actual timings that resulted after installation, this type of comparison has been used to compare emissions. However little research has been conducted on using actual ATCS timings from an operating system and compared the emissions to a TOD plan using a simulation model.

The literature research also revealed little attempts to us traffic simulation software in combination with Emission Models and/or Dispersion Models to predict emission levels at specific sensitive land uses in the corridor in which ATCS was implemented.

Based on this literature review it was concluded that an improved method of estimating emission benefits of an ATCS system, after installation, is needed to determine levels of environmental benefits. This method should be based upon an optimized TOD plan rather than a previously installed TOD which may not reflect current timing needs and is not an accurate comparison of the emission benefits. Also combing traffic simulation emission results with different air quality emission and dispersion models was needed to adequately address the environmental benefits at specific locations in the highway corridor.

3.0 PROPOSED TRAFFIC SIMULATION AND ANALYSIS METHODOLOGY

3.1 SELECTING A MICROSIMULATION MODEL

Several commonly used microsimulation models were selected for review to develop the methodology. Based upon discussions with DOTs and practicing transportation engineering professionals, this comparison was performed for both the PTV Vissim software and Synchro SimTraffic. The models were selected for evaluation because they are commonly used and accepted in the profession.

3.1.1 PTV VISSIM

PTV Vissim is one of several tools available for state-of-art transportation planning and operations analysis. The software was designed to realistically simulate and balance roadway capacity and traffic demand and can be used to evaluate the performance of various traffic conditions. For PTV Vissim provides interfaces to all common controller types such as Sitraffic Office, SCOOT and SCATS, as well as to PTV Visum and PTV Vistro, in order to simulate and fine tune optimized controls.

The add-on module VAP (Vehicle Actuated Programming) can simulate adaptive signal control in PTV Vissim for single intersections, with different strategies for public transport priority up to complex control systems for sub networks. [8] During the simulation, VAP interprets the program instructions of the controller logic and generates appropriate switching commands for the traffic signals. VisVAP (Visual VAP) provides more convenience when defining the controller logic, also allows creating the logic in an easy-to-understand flowchart, using a library of commands for access to signal groups, stages and detectors.

EnViVer is another add-on module for determining pollutant emissions based on vehicle trajectories and other information from PTV Vissim. It is primarily the validity of the speeds and accelerations of the separate vehicles that is crucial for good quality emissions modeling. With PTV Vissim, these can be exported as individual vehicle trajectories to vehicle record files which can be imported into EnViVer for further analysis. Vehicle types are used to assign additional properties such as fuel type or pollutant class to each vehicle in EnViVer. In EnViVer, detailed calculations of CO_2, NOx and PM10 emissions in the area being studied are prepared in graphical or tabular format for an easy-to-understand result.

3.1.2 Synchro and SimTraffic

The Trafficware program Synchro 8 is a powerful, friendly and widely-used traffic software application, which is designed to simulate traffic signal operations of networks on the basis of the HCM methodology. [9] Synchro is a software application for optimizing traffic signal timing and performing capacity analysis. The software optimizes splits, offsets, and cycle lengths for individual intersections, an arterial, or a complete network.

The application is very suitable for evaluating ATCS because it is efficient to change traffic volumes or signal timings and to simulate while playing without resetting the network. Also, the traffic volumes used for the simulation can be imported from an external data file, which documents the 15-minute traffic volumes in a possible network in the CSV (Comma Separated Variable) file format. The optimization function of Synchro is very advantageous and convenient for not only single intersection but also the whole corridor network. Total Cycle Length and Splits can be optimized separately for different research purpose.

SimTraffic performs microsimulation and animation of vehicular traffic. With SimTraffic, Individual vehicles are modeled and displayed traversing a street network. SimTraffic models signalized and un-signalized intersections, and freeway sections. It can also analyze emission data and generate detailed report in specific intersection even each approach.

3.1.3 Summary of Microsimulation Methods

Comparing the PTV VISSIM and Synchro/SimTraffic options, the latter one was selected because it can optimize signal timings both manually and automatically. In order to simulate the ASCT operations a simulation program was needed that the timings could be fixed to replace the ASCT operations. Also the model needed to create a new TOD plan based upon the traffic volume data collected by the ASCT operations. In this circumstance, Synchro is the best choice to simulate operating and optimized conditions.

In comparing the emission evaluation methods of these two software, it was determined that the emission analysis methodology used in Synchro is the same as the node evaluation method in VISSIM, the basis for these are formed by standard formulas for consumption values of vehicles from TRANSYT 7-F, a program for optimizing signal times, as well as data on emissions of the Oak Ridge National Laboratory of the U.S. Department of energy. [9] This methodology will be introduced in the following section.

3.2 SIGNAL CONTROL SYSTEM

3.2.1 TOD Plans optimization

The operations for most existing coordinated signal control systems of corridors and networks are based on Time of Day (TOD) Plans, which operate with or without vehicle/pedestrian detection. Basically, the TOD Plans methodology is to optimize the peak pour's timings then apply them to other hours that have similar traffic patterns based upon manually collected turning movement counts collected just during the peak hours. These timings are then used for the corresponding periods to set the cycle, offset, and splits. These are the key parameters that are typically programmed for anticipated demand at different time periods.

For example, if the optimized analysis period of a traffic signal control system is a 1-hour period, (i.e. the Peak Hour Volume in AM period is the traffic volume from 7:00-8:00 AM), then the optimized timing plan of this hour, which called TOD Plan 1, should be applied into all the AM period from 6:00-9:00 AM thus creating the AM period timing setting. Similarly, the optimized Plans 2 and Plan 3 should be applied into the Mid-Day and PM period, respectively. The optimized Plans 1, 2 and 3 can be developed in microsimulation models like Synchro in such a way that these three traffic performance periods were optimized separately while setting the signal timing for the rest of the hourly network unaltered. [4]

3.2.2 ATCS Plans

Adaptive Traffic Control Systems (ATCSs), also known as real-time traffic control systems, adjust, in real time, signal timings based on the current traffic conditions, demand, and system capacity. The systems require extensive detection, historically in the form of pavement loop detectors, and infrastructure that allows for communication with the central and/or local controllers. There are at least 25 ATCS developments in the United States, [10] all of those play critical roles in operating the traffic signal system. The following figure shows the distribution of ATCSs in U.S., which was updated in 2011. [4]

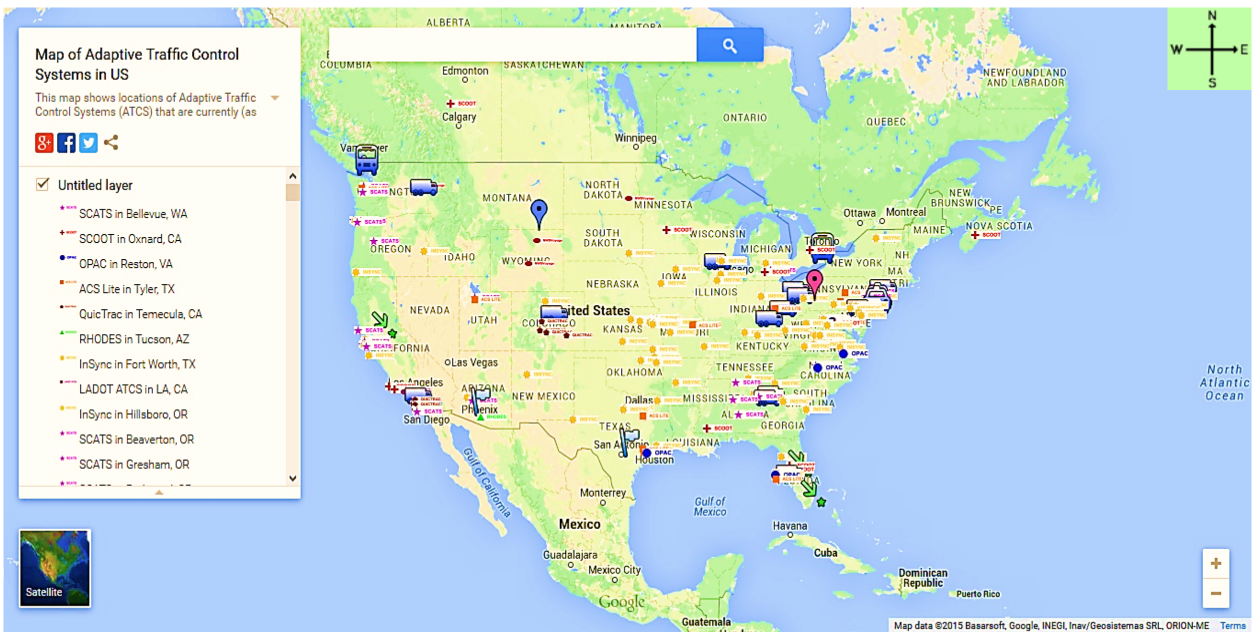

Figure 3-1. Map of Adaptive Traffic Control System in U.S. (2011) [4]

Different ATCS Plans take different strategies to operate signal timing, but they always adjust the traffic patterns based on the real time. The principle of particular ATCS will be introduced in the following sections.

3.3 MODEL CONSTRUCTION AND CALIBRATION

Model construction and calibration is a critical procedure for the methodology which must verify the accuracy of the results, Complete and precise data sources are needed for the simulation of the ATCS corridors. This section introduces the data source and the building of microsimulation model for the methodology.

3.3.1 Data Sources Required

The principle data for building the ATCS corridor microsimulation model includes road and intersection geometric data, traffic flow data and traffic signal operations and timing data. After creating the roads and links of the whole corridors based on the available database and drawings, the traffic volume data must also be input as an Origin-Destination (OD) Matrix. [11] The advantage of building the simulation model from an ATCS is that volume data can get easily obtained as shown in this study. The intersection timing data can be collected from the ATCS data system; in addition, a single day actual timing data is indispensable for the simulation and comparison.

3.3.2 Model Development and Data Input

The model needed to use the methodology and test the research hypothesis can be directly created by using above data sources and also can be imported from other database linkages and systems. The major steps in the model construction include roads and intersections geometry setting, traffic volume estimation and signal groups setting.

Considering the two different types of signal control timing patterns that will be tested, the corridors model will be assigned to two different timing plans for various periods of time. A 12 hours period on an average weekday was selected in this research, because the ATCS comparisons done in other studies only considered peak hour improvements, while many other hours can be expected to benefit and emissions occur during all hours that traffic is present. Also many of the pollutant emission standards are based on 8-hour exposure levels. Thus 12-hour study period can contain all the peak and non-peak hours for meeting both traffic signal timing improvements and pollutant exposure standards requirements. The following Table 3-1 shows the air quality standards according U.S. Environmental Protection Agency (EPA) that are used for transportation environmental impact studies. [12]

Table 3-1. National Ambient Air Quality Standards [12]

Pollutant		**Standard Value**		**Standard Type**
Carbone Monoxide (CO)	8-hour Average	9 ppm	10 mg/m^3	Primary
	1-hour Average	35 ppm	40 mg/m^3	Primary
Nitrogen Dioxide (NO_2)	Annual Arithmetic Mean	0.053 ppm	100 $\mu g/m^3$	Primary & Secondary
Ozone (O_3)	1-hour Average*	0.12 ppm	235 $\mu g/m^3$	Primary & Secondary
	8-hour Average	0.08 ppm	157 $\mu g/m^3$	Primary & Secondary
Lead (Pb)	Quarterly Average		1.5 $\mu g/m^3$	Primary & Secondary
Particulate < 10 micrometers (PM_{10})	Annual Arithmetic Mean		50 $\mu g/m^3$	Primary & Secondary
	24-hour Average		150 $\mu g/m^3$	Primary & Secondary
Particulate < 2.5 micrometers ($PM_{2.5}$)	Annual Arithmetic Mean		15 $\mu g/m^3$	Primary & Secondary
	24-hour Average		65 $\mu g/m^3$	Primary & Secondary
Sulfur Dioxide (SO_2)	Annual Arithmetic Mean	0.03 ppm	80 $\mu g/m^3$	Primary
	24-hour Average	0.14 ppm	365 $\mu g/m^3$	Primary
	3-hour Average	0.5 ppm	1300 $\mu g/m^3$	Secondary

After importing the geometric and traffic volume data into the model, an updated TOD plan should be created by traffic software to get an optimal timing plan; another set of timings will be imported to include the actual ATCS timing data to simulate the ATCS operation.

The TOD plan should be optimized because it cannot be assumed that the previous TOD plan reflects current traffic conditions. Because more recent traffic count data is now available from the ATCS operations this information can be used to create a new hypothetical TOD timing plan. This plan can then be used as the base condition for comparison to the operations with the ATCS timings that are actually in operation. The advantage of this methodology is that the true benefit of the ATCS operations relative to operations and emissions will measured by using the same traffic volumes. Most of the benefit studies reviewed in development of this hypothesis and methodology compared current TOD timing operations to ATCS operations. This is not a true comparison because the TOD may have not been optimized in the recent past. Also they would not have used the same traffic volumes for the optimization as the ATCS collected to create the ATCS timings. This is a critical step and assumption in the methodology.

3.3.3 Model calibration and validation

Model calibration and validation is important for the whole process. After developing the model, some other parameters should be calibrated and validated in the field studies and to calibrate the model for local conditions, the follow data can be collected: speed within intersections, headways between intersections, reactions time to green light. [9]

In order to realistically model traffic it is critical to have realistic Saturated Flow Rates, headways, and speeds. In some cases it may be necessary to change the default parameters to match local driver parameters. Calibrating Yellow Deceleration Rates is also important for timing realistically inputting.

For the calibration, if the Signal Control System is operating TOD Plans, the model can be calibrated in field and then changing the timing plan for achieving the ATCS Plans with the model unaltered; for this research, the Signal Control System is operating the ATCS Plans, so the field study can be done with the ATCS's model and then changing the timing plans of TOD Plans with the model unaltered.

After the calibration and validation of the model, the simulation can be ran for the multiple times. The multiple runs of simulation should be recorded for the whole research period of signal operations. For this methodology multiple runs is 5 times per hour for the 12-hour period is selected because 5 times can be more accurate while the total number of simulation would be 60 times, which the simulator was recommended.

3.4 SUMMARY OF METHODOLOGY

The methodology of this research can be defined and summarized in the following flow-chart in Figure 3-2:

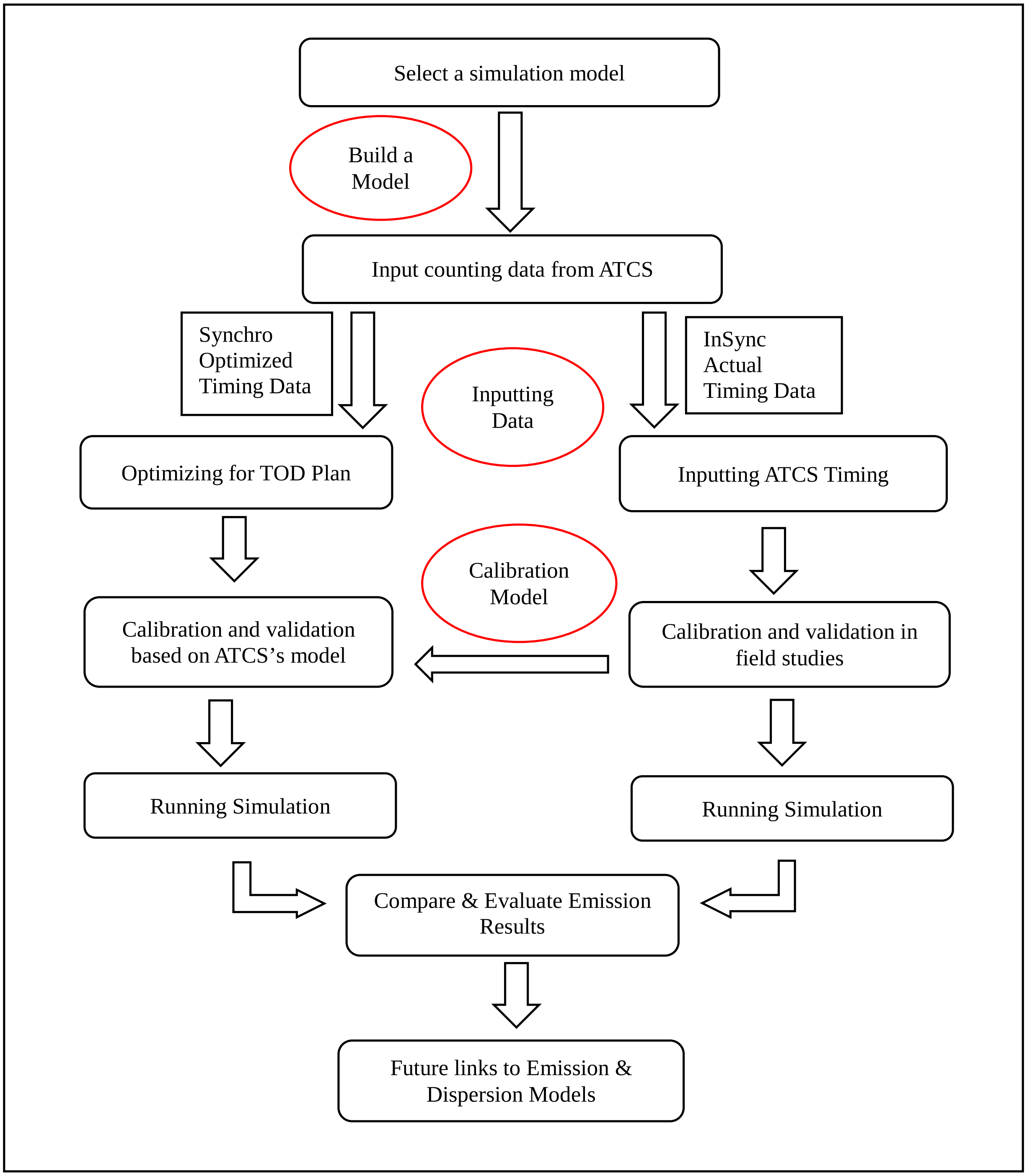

Figure 3-2. Flow-chart of the methodology

4.0 TESTING OF METHODOLOGY AND RESULTS

The Following section reports the testing of the hypothesis using actual modeling and emission data for comparison between the system operating with TOD Plans and InSync Plans using the Synchro simulation model. As a result, the emission results was then compared and analyzed.

4.1 SELECTING AN EXISTING SIGNAL CONTROL SYSTEM FOR TESTING

The existing signalized corridor was selected as a test bed due to its representative nature. The corridor is typical of locations where ATCS is being installed across the United States.

4.1.1 Existing corridor

Once the methodology was developed it was tested on 8-intersections network system which currently operates with the InSync ATCS in the Route 19 corridor (Perry Highway), in Wexford, Pennsylvania. This corridor was selected for testing because it was a recent installation and the Pennsylvania Department of Transportation (PennDOT) made available the data needed for the operations of the system. It was also selected because it represents the typical corridor installation that is being installed currently in many suburban areas in the United States. [10]

The Following map shows the location and situation of the research corridor, as showed in Figure 4-1, in the Pittsburgh roadway system. The corridor is a north south commuting and retail corridor between the Downtown Central Business District (CBD) Pittsburgh and northern suburbs of Pittsburgh. This corridor has travel demand characteristics that increase rapidly during the peak hours especially the AM Peak Hour and PM Peak Hour but also remains high and steady during daytime off peak hours and evenings due to the retail activity in the corridor.

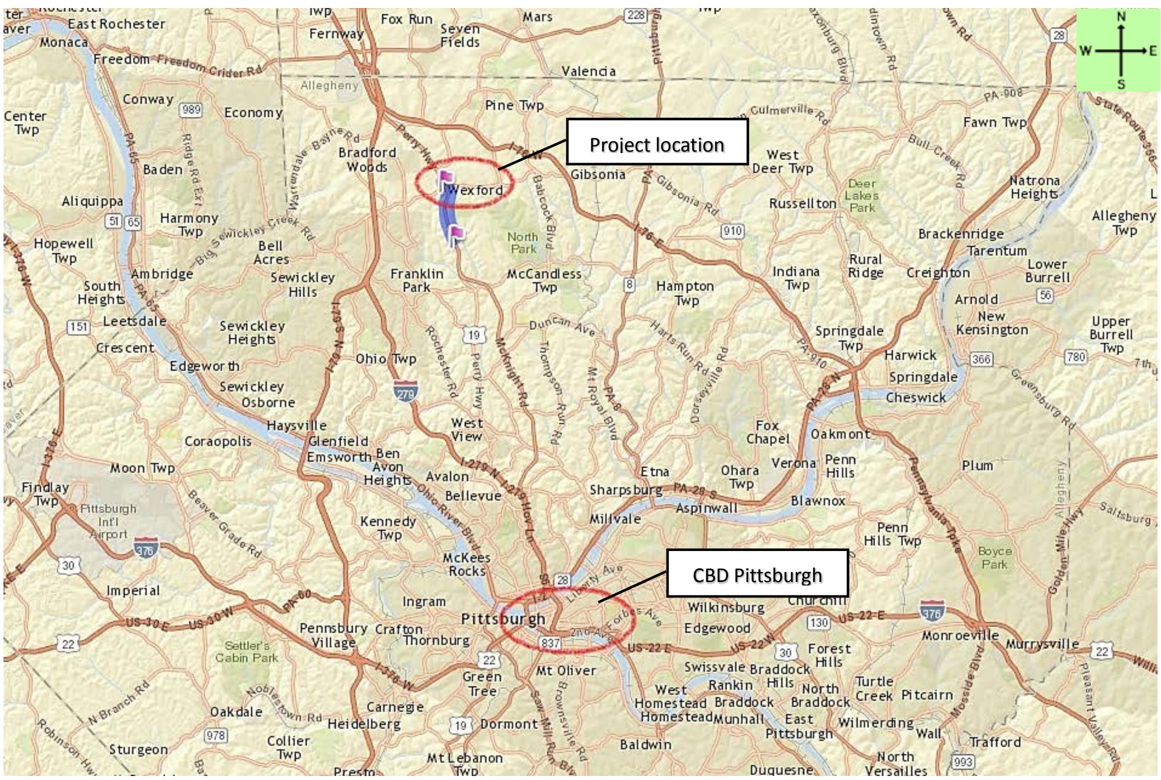

Figure 4-1. The location of research corridor (National Geographic Mapmaker Interactive)

This corridor was also selected because there are specific sensitive air quality receptor sites which include commercial, school, church, and residential land uses in the corridor. These sites including all the 8 intersections were all marked in the following figure 4-2. This is a wide range of land uses that would be desirable to testing, when considering the benefits from emissions reductions on those specific sensitive sites.

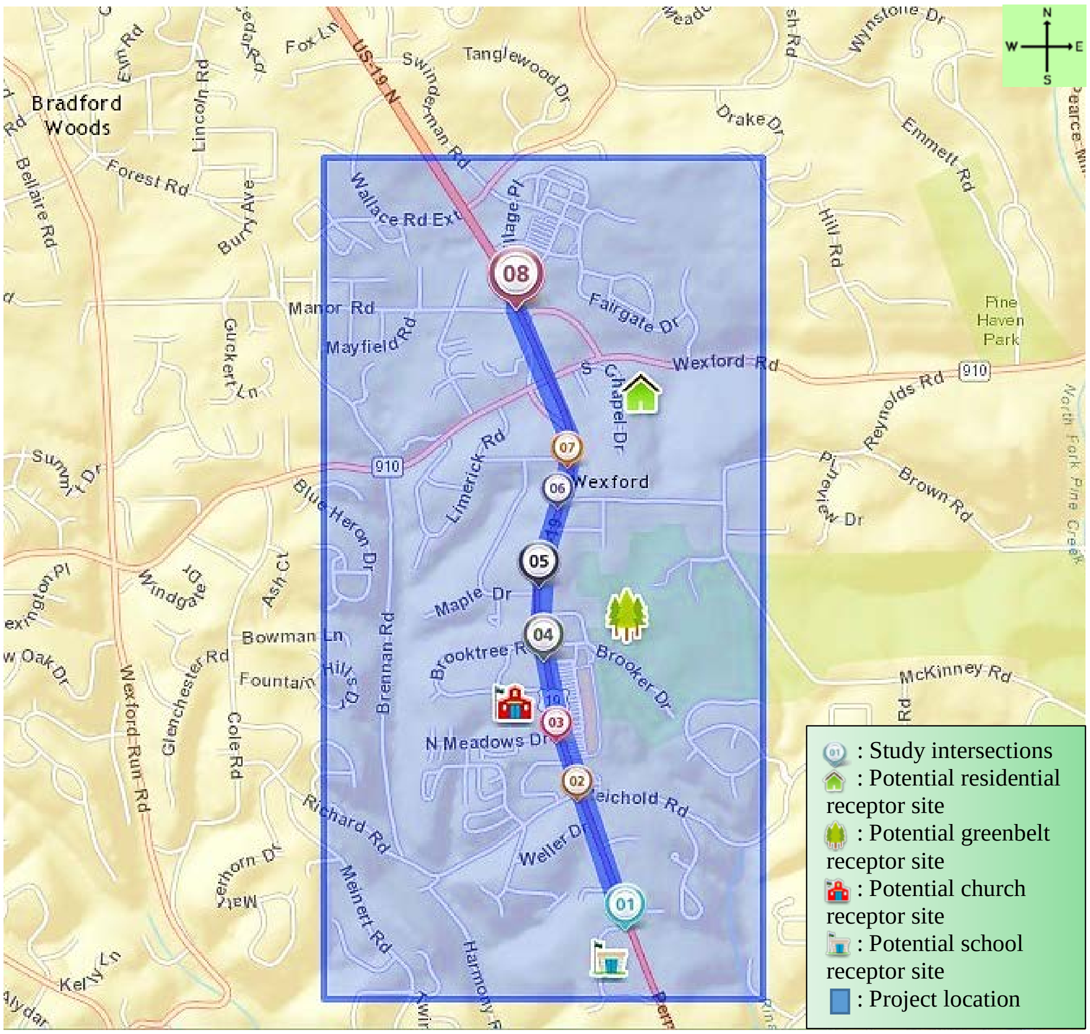

Figure 4-2. Detailed situation of the corridor (National Geographic Mapmaker Interactive)

The following intersections are integrated into the ATCS along Route 19 (Perry Highway): North Allegheny Senior High School/ Drive; SR 0019; SR (State Route) 4053 (Richard Road)/ Reichold Road; North Meadow Drive/ Wexford Plaza Drive; Brooktree Road (T-917)/ Brooker Drive (T-844); Wright Pontiac Driveway/ Wexford Flats Plaza Driveway;

Brown Road (T-6911)/ Pine Centre Driveway; Bonnie View Drive (T-513)/ Baierl Cadillac Driveway; and SR 4073 (North Caper Road)/ Manor Road (T-697). Table 4-1 shows all the 8 intersections basic information on volumes and operations.

Table 4-1. Basic information of all the intersections in InSync System of Wexford, PA

NO.	Name of the intersection crossed by R19	No. of phases	No. of Approach lanes	Total 12hr approach volume
1	North Allegheny High School Driveway	6	10	27,199 veh
2	Richard Road (State Route 4053) / Reichold Road	6	10	29,925 veh
3	North Meadows Drive / Wexford Plaza Driveway	7	10	31,840 veh
4	Brooktree Road / Brooker Drive	7	10	28,189 veh
5	Wexford Flats Plaza Driveway / Wright Pontiac Driveway	6	8	21,463 veh
6	Brown Road / Pine Center Driveway	6	9	23,764 veh
7	Bonnie View Drive / Baierl Oldsmobile Cadillac Driveway	6	9	21,028 veh
8	SR 0019 & North Chapel Road / Manor Road/ Church Road	7	10	31,981 veh

4.1.2 Conventional Signal Control System Baseline Operations

An optimized TOD operation for the corridor, which was in place prior to installation of the ATCS was simulated, for the 8-intersections based on the traffic volume counts obtained from the InSync operations. For this test, 12 hours of count data, from 7:00am to 7:00pm on September 10th, 2014 was chosen as the analysis time period. This was selected because it was a Wednesday in September which represents near typical conditions for this type of roadway.

Three hours representing typical peak hours were selected for development of the TOD Plans. Table 4-2 shows the hours that were selected to develop the plan and the hours' optimized timings were applied to adjacent to those hours. This is a typical TOD plan development methodology. Representative hours are selected in each intersection and then the timings are applied to other hours assuming similar traffic flow characteristics, the optimized hourly timings Plan 1, 2 and 3 represent the 12-hour research period's signal timings which include AM, Mid-Day and PM typical timing plans from 7:00 AM to 7:00 PM on a weekday.

The detailed time intervals and hours used for optimization are showed as following Table 4-2. Plan 1 (AM) is the optimized hourly timing plan based on all the intersections' peak hours counting data (there are various peak hours' selection of all the intersections) from 7:00 am to 9:00 am. Plan 2 (Mid-Day) is the optimized hourly timing plan from 9:00am to 4:00pm and it was applied to the 7 hours identified. Plan 3 is the optimized hourly timing plan for the rest of PM time and is applied to these three hours shown.

Table 4-2. Detailed time intervals and corresponding plan

Time of day	Optimized plan
7:00-8:00	Plan 1 (AM)
8:00-9:00	
9:00-10:00	Plan 2 (Mid-Day)
10:00-11:00	
11:00-12:00	
12:00-13:00	
13:00-14:00	
14:00-15:00	
15:00-16:00	
16:00-17:00	Plan 3 (PM)
17:00-18:00	
18:00-19:00	

4.2 ADAPTIVE SIGNAL CONTROL SYSTEMS

The InSync Adaptive Signal System, which was developed by Rhythm Engineering, has grown in acceptance and popularity recent years, especially in the eastern U.S. This ATCS uses a new methodology to optimize timings on a real time basis. The system combines accepted algorithms from multiple fields of engineering and applies them to traffic volume data, to create more efficient signal timings. [13]

The InSync System uses a fundamentally different system of controlling and optimizing signal phases and timings in real-time, the methodology is innovative and relatively simple.

InSync performs optimization at two levels, the local level and the global level. [13] The global level is focused on creating platoons and moving these platoons through a corridor with the highest level of efficiency possible by focusing on progression. While Rhythm Engineering refers to them as "time tunnels", traffic engineers know them as green bands on time/space diagrams. The global optimizer works to group platoons and optimize their progression by ensuring that when each time tunnel reaches an intersection, the intersection will be green at that time. This may mean that the global optimizer will force the start of the green phase or that it will ensure that an already green signal remains green for the approaching platoon. What each local signal does in between the time tunnels is up to the local optimizer. Traditional interconnected timing plans to coordinate all of the signals in the system are not required, so a common cycle length is also not required, nor are timing plans in any traditional sense of the phrase. As there are no timing plans to switch to and from, there is no transition time required for all of the signals in a system to return to coordination.

The local intersection is required to serve specific phases associated with the time tunnel based on the global optimizer. [13] This phase may be served by one or more states in a sequence. Outside of the time specified by the global optimizer, each intersection runs its own optimization at the local level. Its optimization algorithm accounts for volume and delay and is based on a modified greedy algorithm. Parameters can be adjusted to give higher priority certain phases, such as when a signal is received from an approaching transit bus. The local optimizer allows each signal in the corridor to operate as if it was a “smart” fully actuated controller during the time that the signal is not being controlled by the global optimizer. The fact that each signal is run using a digital architecture means that phases can be served multiple times between the global platoons, something a traditional analog adaptive or non-adaptive system cannot do. The manner in which the system operates means that platoon progression on the main street is optimized while allowing the local intersections to serve side street demand far more efficiently than typical coordinated systems as well as other adaptive signal systems.

4.3 THE METHEODOLOGY OF EMISSION ANALYSIS

Emission analysis for the traffic corridor test bed is critical and estimating the pollutants is the first step to measure the benefits due to ATCS. The common pollutants of traffic emissions include the following ones: [3]

Sulfur oxides (SOx) are chemical compounds which is one of the causes of acid rain; Nitrogen oxides (NOx), especially nitrogen dioxide are emitted from high temperature combustion, which can be seen as the brown haze dome above or plume downwind of cities. NO_2 is one of the most prominent air pollutants; Carbon monoxide (CO) is a colorless, odorless, non-irritating but very poisonous gas. Vehicular exhaust is a major source of carbon monoxide.

Carbon dioxide (CO_2) is a greenhouse gas emitted from combustion. Volatile organic compounds (VOCs) are an important outdoor air pollutant. Some compounds (benzene, toluene and xylene) are suspected carcinogens and may lead to leukemia through prolonged exposure. 1, 3-butadiene is another dangerous compound which is often associated with industrial uses.

Particulates, alternatively referred to as particulate matter (PM) or fine particles, are tiny particles of solid or liquid suspended in a gas. In contrast, aerosol refers to particles and the gas together. Sources of particulate matter can be manmade or natural. Those made by human activities—currently account for about 10 percent of the total amount of aerosols in our atmosphere. Increased levels of fine particles in the air are linked to health hazards such as heart disease, altered lung function and lung cancer, which is a result of those pollutants.

In this research, some of these pollutants are estimated by the simulator including CO, NOx and HC. The methodology used by microsimulation software, like Synchro and VISSIM to generate emission data is listing as following steps:

A key assumption in estimating emissions is how much fuels is being consumed in a corridor or a roadway network during the simulation period. Fuel consumption is calculated by several of the simulation programs using the following empirical formulas based on: [4]

$$F = TotalTravel \times k1 + TotalDelay \times k2 + Stops \times k3$$

$$k1 = 0.075283 - 0.0015892 \times Speed + 0.00015066 \times Speed^2$$

$$k2 = 0.7329$$

$$k3 = 0.0000061411 \times Speed^2$$

F = Fuel consumed in Gallons

Speed = Cruise speed in Mph

Total Travel = Vehicle miles traveled

Total Delay = Total signal delay in hours

Stops = Total stops in vehicles per hour

This formula to estimate fuel consumption used by Synchro, VISSIM and TRANSYT 7-F. The emissions calculations for these simulation programs are based only on fuel consumption. This somewhat simplifies the calculation by using the following factors to determine emission rates:

$$CO = F \times \frac{69.9g}{gal} = Carbon\ Monoxide\ Emissions\ (g)$$

$$NOx = F \times \frac{13.6g}{gal} = Nitrogen\ Oxides\ Emissions\ (g)$$

$$VOC = F \times \frac{16.2g}{gal} = Volatile\ Oxygen\ Compounds\ Emissions\ (g)$$

These simplified rates are based on an unpublished letter to the Federal Highway Administration from Oak Ridge National Labs. [9] However for purpose of this research to measure the comparative benefits of a TOD plan and an ATCS plan this was considered to be sufficient.

4.4 ADAPTING THE SYNCHRO MODEL TO TEST THE HYPOTHESIS

Synchro was selected not only because it is a software application for optimizing traffic signal timing; but also the SimTraffic application is efficient when changing traffic volumes or signal timings in longer time periods. Synchro and SimTraffic are suitable platforms to evaluate ATCS. They can provide the basic tools to evaluate delays and emissions while they cannot directly import and analyze ATCS timings. Other software tools maybe available to address the variable nature of ATCS, but Synchro was selected because of it is common use by traffic engineers. This research determines how to modify the methods of these platforms for the use in the evaluation of ATCS systems. As a result, Synchro was selected for the microsimulation model to test the hypothesis in this research.

4.4.1 Counting data collection

The actual counting data of the 8 intersections on Sep. 10th, 2014 was collected from the InSync system, the traffic volume hourly counts by hour from 7:00 am to 7:00 pm were downloaded by Rhythm Engineering and provided to the researcher. The counting data, as shown Table 4-3, was then reviewed and the volume for each movement was adjusted based on the distribution factors from counting data obtained from 2012. The 2012 data was manually obtained and included separate counts for shared lanes. This adjustment is necessary because the InSync system only counts lane volumes. Lanes with shared movements (right and through traffic) requires adjustment factors. That's to say a southbound through lane (SBT) contains the volume of SBT and southbound right (SBR). Thus a distribution factor is needed for shared movement lanes which calculates the all movements for the traffic volumes.

Table 4-3. Example of Original actual counting data from Rhythm Engineering for the 1st intersection

Turning Movement Counts						
	SBL	**NBT**	**EBT**	**NBL**	**SBT**	**WBT**
Time	Phase 1	Phase 2	Phase 4	Phase 5	Phase 6	Phase 8
7:00 AM	2	172	46	178	263	39
7:15 AM	1	272	42	41	163	96
7:30 AM	3	315	9	16	194	191
7:45 AM	2	269	3	31	177	154
Total	8	1,028	100	266	797	480
8:00 AM	1	256	6	15	108	64
8:15 AM	0	170	18	11	130	42
8:30 AM	6	89	8	51	107	45
8:45 AM	2	217	2	11	82	24
Total	9	732	34	88	427	175

Table 4-4 is an example of counting data for the 7:00-8:00 am of the first 7 intersections after calculation for each movements, the 8th intersection is listed separately as Table 4-5 because it is a more complicate intersections with 5 approaches and more movements for each approach.

Table 4-4. Counting data for 7 intersections in InSync System on 7:00-8:00 AM

7:00-8:00	**North Allegheny High School Driveway**	**Richard Road (State Route 4053) / Reichold Road**	**North Meadows Drive / Wexford Plaza Driveway**	**Brooktree Road / Brooker Drive**	**Wexford Flats Plaza Driveway / Wright Pontiac Driveway**	**Brown Road / Pine Center Driveway**	**Bonnie View Drive / Baierl Oldsmobile Cadillac Driveway**
SBR	166	8	23	104	3	0	42
SBT	631	647	720	777	791	896	568
SBL	8	51	116	18	19	49	0
	805	706	859	899	813	945	610
WBR	49	83	35	22	0	56	13
WBT	322	20	3	15	0	3	0
WBL	109	114	53	10	37	48	2
	480	217	91	46	37	108	14
NBR	11	20	41	0	2	11	5
NBT	1,017	546	852	590	461	559	602
NBL	266	127	35	87	0	5	41
	1,294	693	928	677	463	575	648
EBR	65	193	88	16	14	53	14
EBT	0	36	6	3	0	4	1
EBL	35	155	31	88	2	0	23
	100	384	124	107	16	57	38

Table 4-5. Counting data for the 8th intersection in InSync System on 7:00-8:00 AM

(*M stands for Manor Road; **C stands for Church Road)

	SBR-M*	**SBR-C****	**SBT**	**SBL**		**WBR**	**WBT**	**WBL-19**	**WBL-C**					
7:00-8:00	35	140	724	36	935	112	0	122	30	264				
	NBR	**NBT**	**NBL-M**	**NBL-C**		**EBR-19**	**EBR-C**	**EBT**	**EBL**		**CBR**	**CBT**	**CBL**	
7:00-8:00	5	490	10	1	506	140	35	0	119	295	20	40	12	72

The counting data was used to optimize the TOD Plans by comparing AM, Mid-Day and PM period traffic volumes for the 12 hours, and the peak 15 minutes for AM, Mid-Day and PM, separately, to be selected the single highest hourly traffic volumes which is the basis to generate Plans 1, 2 and 3 in Synchro. Then Plan 1, 2 and 3 was applied to the corresponding period unaltered.

4.4.2 Actual Timing Data Collection and Adaption

The actual timing data for the InSync signal control system on Sep 10th, 2014 was downloaded by Rhythm Engineering and summarized by the researchers. The data consists of the green duration shown directly of each operating cycle. This detailed data on the operations used for each cycle needed to be aggregated because the Synchro model’s typical analysis period is one hour. Therefore a method was needed and developed that converted the varying cycle timings as a representative operation for a one hour period. An aggregation method was developed for this purpose.

For the aggregation method, the mean green time of each phase was calculated and combined into a timing cycle with all-red and yellow timing data, which was used to define the timing profile required for the representative timing data. This was done for the one hour analysis period no matter how long the operating cycle length. As an example, the following Table 4-6 shows the operating splits timing data of the No. 4 intersection, SR19 & Brooktree St and Brooker St. Each cycle has been split and total duration for each cycle has been aggregated. As the table shows each cycle has a maximum cycle length of 124 seconds, but this was not the limitation for the actual representative timing data due to the strategies of InSync operation.

Table 4-6. Original splits timing data for SR19 & Brooktree St &Brooker (half hour timing data.

*Percentage here means the specific phase duration take how much of the total duration in one hour)

Date	Time	Movements	Green time duration(s)	Max Cycle length(s)	Total green time duration(s)	percentage*
9/10/2014	6:58:41	NT/ST	100	124	**115**	2.98%
9/10/2014	7:00:27	WT	8			0.24%
9/10/2014	7:00:40	ET	7			0.21%
9/10/2014	7:00:52	NT/ST	217	124	**224**	6.47%
9/10/2014	7:04:35	ET	7			0.21%
9/10/2014	7:04:47	NT/ST	119	124	**126**	3.55%
9/10/2014	7:06:52	ET	7			0.21%
9/10/2014	7:07:04	NT/ST	92	124	**106**	2.74%
9/10/2014	7:08:42	WT	7			0.21%
9/10/2014	7:08:54	ET	7			0.21%
9/10/2014	7:09:06	NT/ST	101	124	**109**	3.01%
9/10/2014	7:10:53	WT	8			0.24%
9/10/2014	7:11:06	NT/ST	107	124	**115**	3.19%
9/10/2014	7:12:59	ET	8			0.24%
9/10/2014	7:13:12	NT/ST	107	124	**116**	3.19%
9/10/2014	7:15:05	ET	9			0.27%
9/10/2014	7:15:19	NT/ST	94	124	**109**	2.80%
9/10/2014	7:16:59	WT	8			0.24%
9/10/2014	7:17:12	ET	7			0.21%
9/10/2014	7:17:24	NT/ST	100	124	**107**	2.98%
9/10/2014	7:19:10	ET	7			0.21%
9/10/2014	7:19:22	NT/ST	102	124	**131**	3.04%
9/10/2014	7:21:10	WT	13			0.39%
9/10/2014	7:21:28	SL/NL	7			0.21%
9/10/2014	7:21:41	ET	9			0.27%
9/10/2014	7:21:55	NT/ST	70	124	**77**	2.09%
9/10/2014	7:23:11	ET	7			0.21%
9/10/2014	7:23:23	NT/ST	113	124	**140**	3.37%
9/10/2014	7:25:22	WT	7			0.21%
9/10/2014	7:25:34	ET	7			0.21%
9/10/2014	7:25:46	NT/NL	7			0.21%
9/10/2014	7:25:53	NT	6			0.18%
9/10/2014	7:25:59	NT/ST	74	124	**81**	2.21%
9/10/2014	7:27:19	ET	7			0.21%
9/10/2014	7:27:31	NT/ST	106	124	**117**	3.16%
9/10/2014	7:29:23	ET	11			0.33%
Total Green time for 1hr (7:00-8:00)					**3354**	100%

The percentage showed in the above table shows how much of the particular phase was the percent of the green time in the whole 1-hour research period. The total percentage for each phase was generated by summing each percentage of the particular movement. The average green time for each phase was then calculated by using the total green duration in 1 hour and each phase's percentage. As results of the aggregation, the representative cycle phase was generated as following Table 4-7 shows. The cycle length for every intersection is various and there is even 452 cycle length in this ATCS representative timing plan.

Table 4-7. Average green time each cycle on 7:00-8:00 am hour for the ATCS

	Phase	**1**	**2**	**4**	**5**	**6**	**8**	**Cycle Length (s)**
		SBL	NBT	EBT	NBL	SBT	WBT	
1 SR19_NASH	7:00-8:00	0	135	5	5	131	5	152
2 SR19_Richard_Reichold	7:00-8:00	2	76	23	5	73	23	111
3 SR19_N_Meadows_Wexford_Plaza	7:00-8:00	4	91	13	0	95	13	111
4 SR19_Brooktree_Brooker	7:00-8:00	1	107	8	3	105	4	122
5 SR19_Wright_Pontiac	7:00-8:00	0	437	8	0	437	8	452
6 SR19_Brown_Rd	7:00-8:00	1	95	22	1	95	22	119
7 SR19_Bonnieview	7:00-8:00	0	411	7	2	409	7	425
8 SR19_NChapel_Manor	7:00-8:00	8	55	21	7	56	22	106

The control type of timing setting is Semi-Actuated-Uncoordinated which can realistically simulate the InSync Plans timing methods. A semi-actuated signal recalls the main street through phases to their Maximus values, other assigned phases may skip or gap-out based on vehicle detection. This signal is not considered coordinated because the cycle length can vary each cycle.

4.4.3 Inputting Data into the Synchro Model

After collating all the counting and timing data for the InSync System, the data was input into the 8-intersections Synchro model built for the simulation.

The model was run for two different scenarios for the various periods of time after importing the geometric and traffic volume data; one scenario was optimized by Synchro to get an optimal TOD timing plan, then applied them to corresponding hours; another scenario was to import actual ATCS timing data hour by hour, modified for analysis purposes, to simulate the ATCS operation.

The typical interface after inputting all the data of the corridor shows as following Figure 4-3. The PHF for each movement was set based on the counting data, travel speed was set based on the speed limitation of each lane, Heavy Vehicle was set to 2%-20% based on the intact counting data in 2012 and Growth Factor was set to 1.00 for all.

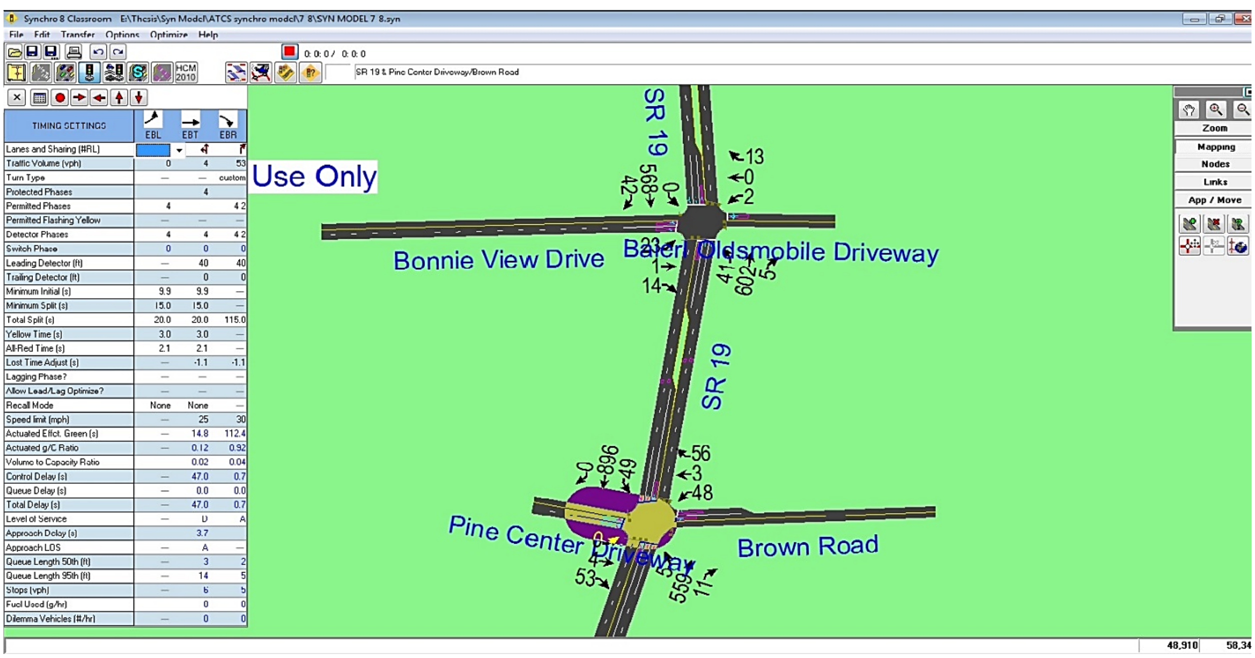

Figure 4-3. Synchro Model interface of the ATCS corridor

Five runs of simulation were recorded for each hour of the twelve hour research period. The reports were generated based on the simulation and emission data which are analyzed in the following section. The typical SimTraffic interface is shown in following figure 4-4.

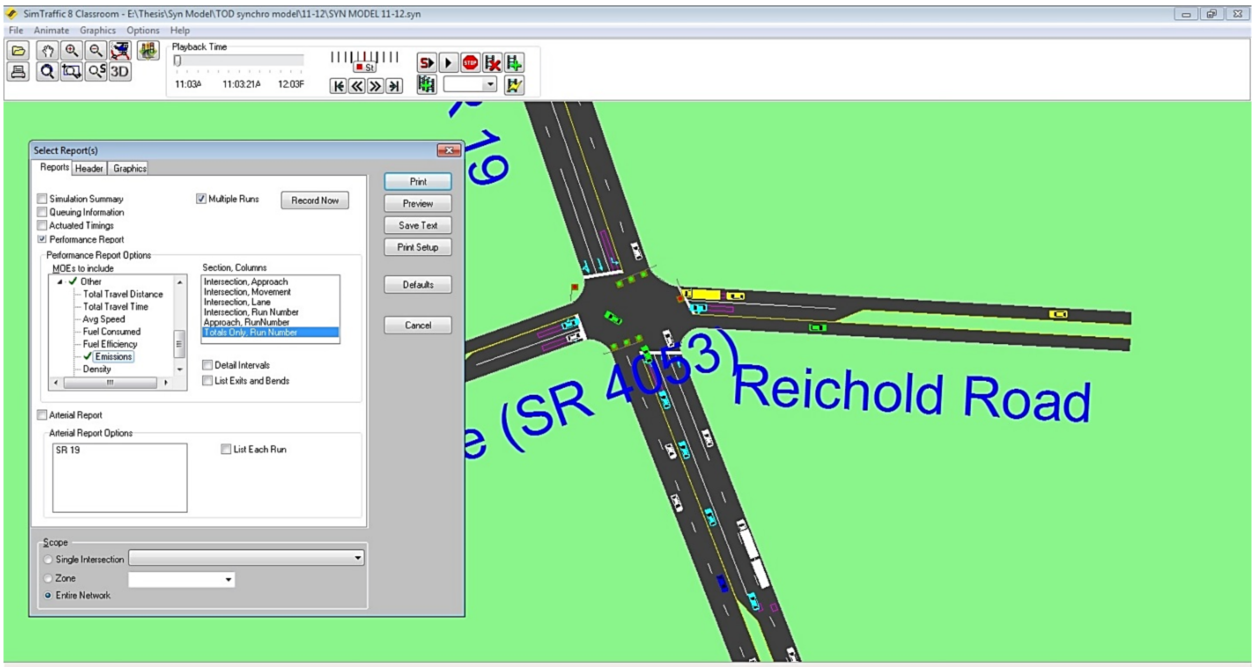

Figure 4-4. SimTraffic interface and the report generator

4.5 SYNCHRO MODEL OUTPUT RESULTS

4.5.1 Simulation results

The simulation was run for the 8-intersection corridor network in each single hour, from 7:00 am to 7:00 pm. The 12-hour period performance was recorded for comparison purposes. The performance can be reported as detailed as actual signals timings, observed splits, total delay, total stops, emissions and fuel consumption, etc. The Time Space Diagrams generated for one hour for both the TOD and ATCS outputs shows as following.

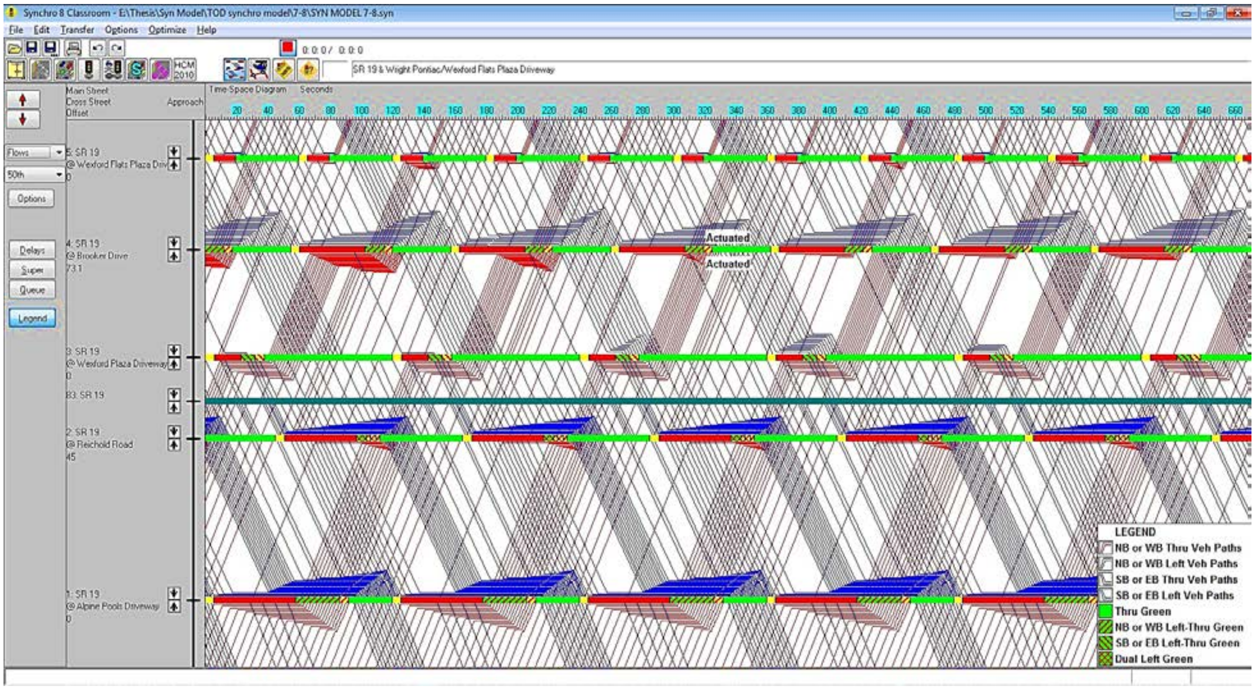

Figure 4-5. Time Space Diagram for 7-8 am of TOD operation

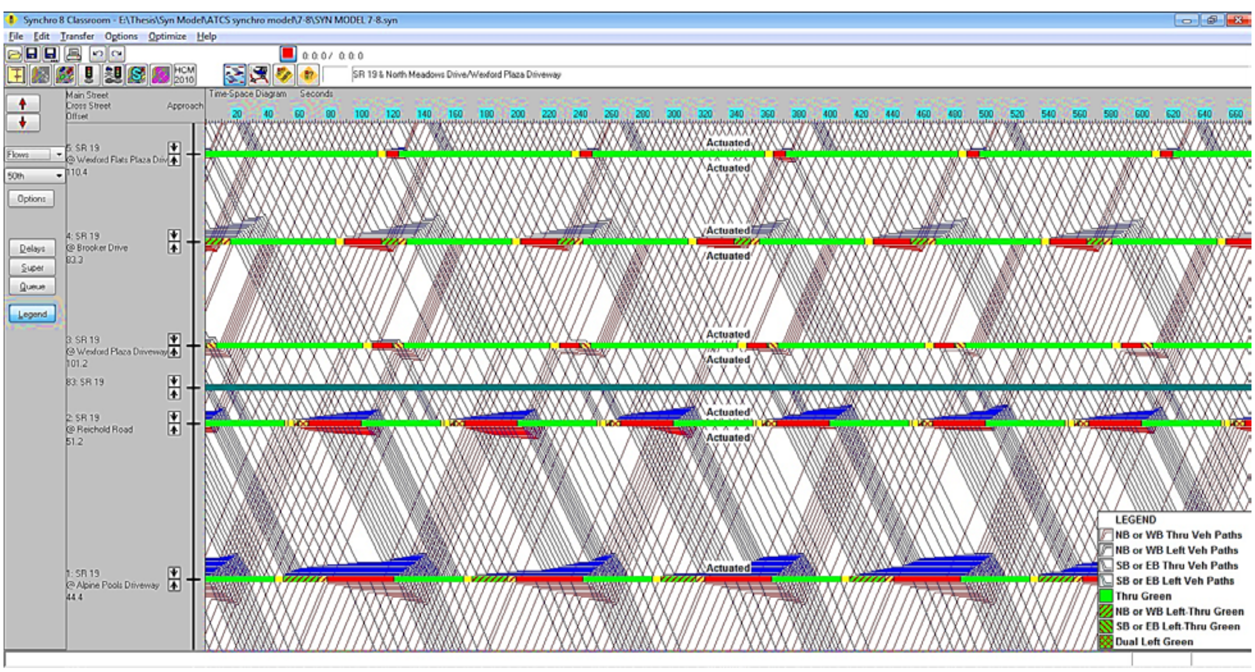

Figure 4-6. Time Space Diagram for 7-8 am of ATCS operation

From the Time Space Diagram of ATCS operation, the cycle length varies when compared with the Time Space Diagram of TOD operation. The benefit of ATCS is that it can maintain progression with non-uniform intersection spacing and different cycle lengths. In conclusion, the progression with ATCS operation can be significantly maintained.

However, according to the hypothesis and research objective, only the emission results were evaluated. The following is a summary of the results.

The emission results contain both the TOD and InSync timing plans. The TOD Plans emission results for two representative hours are shown in Tables 4-8 and 4-9. The results are also shown for the entire corridor in Table 4-10. For purposes of testing the hypothesis the total corridor results are considered to be more representative of the overall change in emission levels than individual intersections.

Table 4-8. TOD Plans on 7:00-8:00 am network emission performance

SimTraffic Performance Report (TOD Plans)						
Total Network Performance By Run						
Run Number	1	2	3	4	5	Avg
HC Emissions (g)	2,060	2,064	1,982	2,029	2,028	2,033
CO Emissions (g)	52,615	52,621	51,216	52,665	51,397	52,103
NOx Emissions (g)	6,491	6,505	6,250	6,442	6,307	6,399

Table 4-9. TOD Plans on 8:00-9:00 am network emission performance

SimTraffic Performance Report (TOD Plans)						
Total Network Performance By Run						
Run Number	1	2	3	4	5	Avg
HC Emissions (g)	1,865	1,836	2,001	1,889	1,833	1,885
CO Emissions (g)	50,087	49,842	52,169	50,208	48,749	50,211
NOx Emissions (g)	5,975	5,894	6,320	6,024	5,873	6,017

The model also reported emissions for 12 the hours selected, which includes HC, CO and NOx emissions. Table 4-10 shows the pollutants estimated during the 12-hour simulation:

Table 4-10. TOD Plans Emissions results during 12-hour simulation

	TOD HC Emissions (g)	TOD CO Emissions (g)	TOD NOx Emissions (g)
7:00-8:00	2,033	52,103	6,399
8:00-9:00	1,885	50,211	6,017
9:00-10:00	1,748	48,130	5,605
10:00-11:00	1,835	49,945	5,880
11:00-12:00	2,167	60,602	7,106
12:00-13:00	2,434	67,577	7,991
13:00-14:00	2,694	72,666	8,626
14:00-15:00	3,108	80,283	9,741
15:00-16:00	3,282	89,266	8,804
16:00-17:00	3,271	85,482	10,218
17:00-18:00	3,337	88,420	10,496
18:00-19:00	2,735	70,898	8,344

Figure 4-5 shows the total emissions for the 12-hour simulation based on the three pollutants emission results of the TOD System.

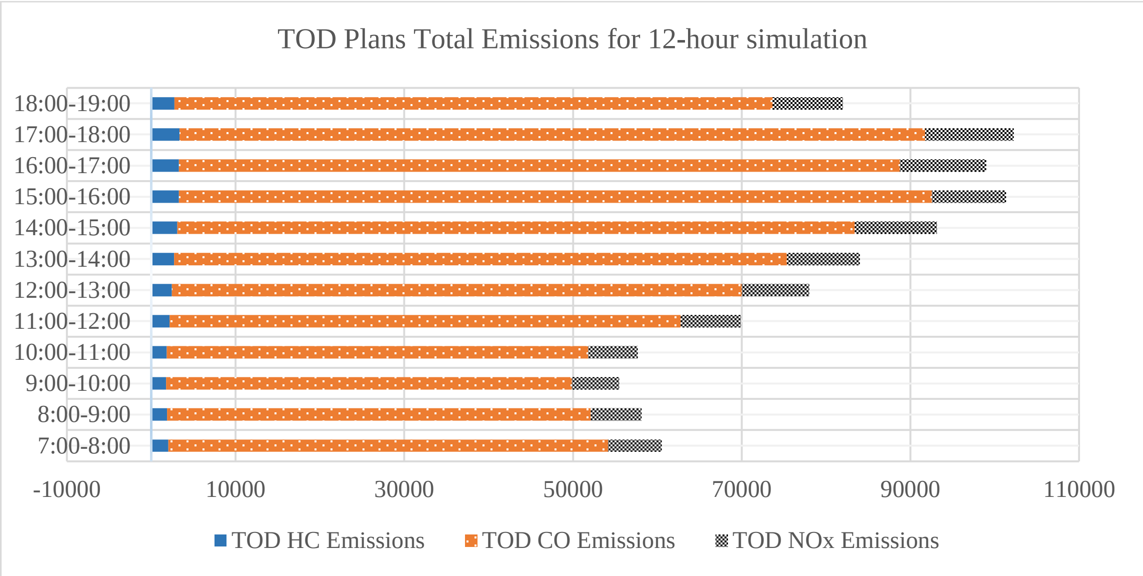

Figure 4-7. Emissions for TOD Plans operating system

The results show a trend of all emissions increasing from about 9:00 am to 12:00 pm during this day, then there is a decreasing trend. It can be concluded that the PM Peak Hour is more significant than the others and causes the greatest amount of emissions.

In another scenario, the simulation of actual ATCS timing signal data has run for all the 12 hours. The InSync Plans emission results show as below in Table 4-11 and 4-12:

Table 4-11. InSync Plans on 7:00-8:00 am network emission performance

SimTraffic Performance Report (InSync Plans)						
Total Network Performance By Run						
Run Number	1	2	3	4	5	Avg
HC Emissions (g)	1,922	1,987	2,083	1,852	1,916	1,952
CO Emissions (g)	49,737	50,902	52,100	48,329	48,981	50,010
NOx Emissions (g)	6,041	6,173	6,348	5,812	6,006	6,076

Table 4-12. InSync Plans on 8:00-9:00 am network emission performance

SimTraffic Performance Report (InSync Plans)						
Total Network Performance By Run						
Run Number	1	2	3	4	5	Avg
HC Emissions (g)	1,717	1,779	1,867	1,652	1,828	1,768
CO Emissions (g)	46,948	48,419	49,768	46,207	48,815	48,032
NOx Emissions (g)	5,598	5,706	5,922	5,343	5,837	5,681

The following Table 4-13 shows the three kinds of pollutants estimated for the InSync System during the 12-hour simulation period:

Table 4-13. InSync Plans Emissions results during 12-hour simulation

	InSync HC Emissions (g)	InSync CO Emissions (g)	InSync NOx Emissions (g)
7:00-8:00	1,952	50,010	6,076
8:00-9:00	1,768	48,032	5,681
9:00-10:00	1,695	47,324	5,354
10:00-11:00	1,788	48,967	5,597
11:00-12:00	2087	58,022	6,581
12:00-13:00	2,289	64,621	7,362
13:00-14:00	2,633	70,788	8,025
14:00-15:00	2,832	76,104	8,610
15:00-16:00	2,956	84,031	7,982
16:00-17:00	2,972	81,097	8,632
17:00-18:00	3,003	83,619	8,277
18:00-19:00	2,567	67,868	7,375

Figure 4-6 shows the total emissions for the 12-hour simulation based on the three pollutants emission results of the InSync System.

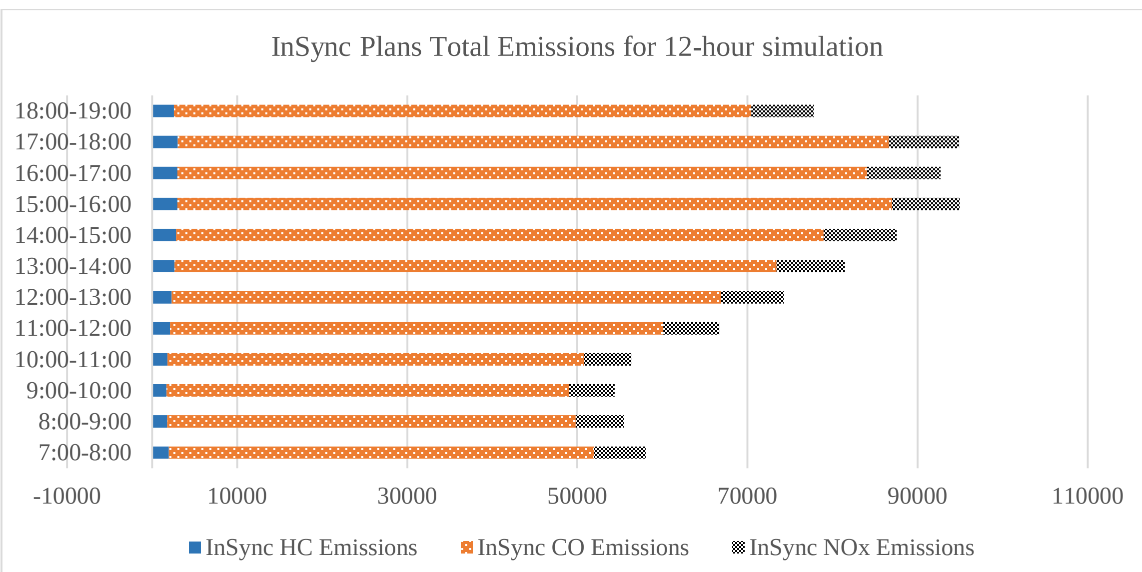

Figure 4-8. Emissions for InSync Plans operating system

The conclusion can be obviously stated that the trend of those pollutants also increase from around 9:00 am to 6:00 pm, then there is also have a decreasing trend. The InSync operating system estimates similar emissions tendency as the TOD Plans.

4.5.2 Comparison of emissions results

For better analyzing the reduction of different kind of pollutants, the percentage of each pollutant's reduction during a one hour period when comparing TOD to the InSync operation is shown in Table 4-14. It can be concluded that the NOx has the most significantly reduction among the three.

Table 4-14. Reduction percentage of each emission result

Time	HC Emissions	CO Emissions	NOx Emissions
7:00-8:00	3.98%	4.02%	5.05%
8:00-9:00	6.21%	4.34%	5.58%
9:00-10:00	3.03%	1.67%	4.48%
10:00-11:00	2.56%	1.96%	4.81%
11:00-12:00	3.69%	4.26%	7.39%
12:00-13:00	5.96%	4.37%	7.87%
13:00-14:00	2.26%	2.58%	6.97%
14:00-15:00	8.88%	5.21%	11.61%
15:00-16:00	9.93%	5.86%	9.34%
16:00-17:00	9.14%	5.13%	15.52%
17:00-18:00	10.01%	5.43%	21.14%
18:00-19:00	6.14%	4.27%	11.61%
Average	5.98%	4.09%	9.28%

According to the reduction percentage, the following charts were generated to compare the emission quantity of the three pollutants. For the TOD Plans and InSync Plans emission data, the reduction percentage was also add to the chart for comparison purposes. The comparison of each kind of pollutant shows as following Figure 4-7.

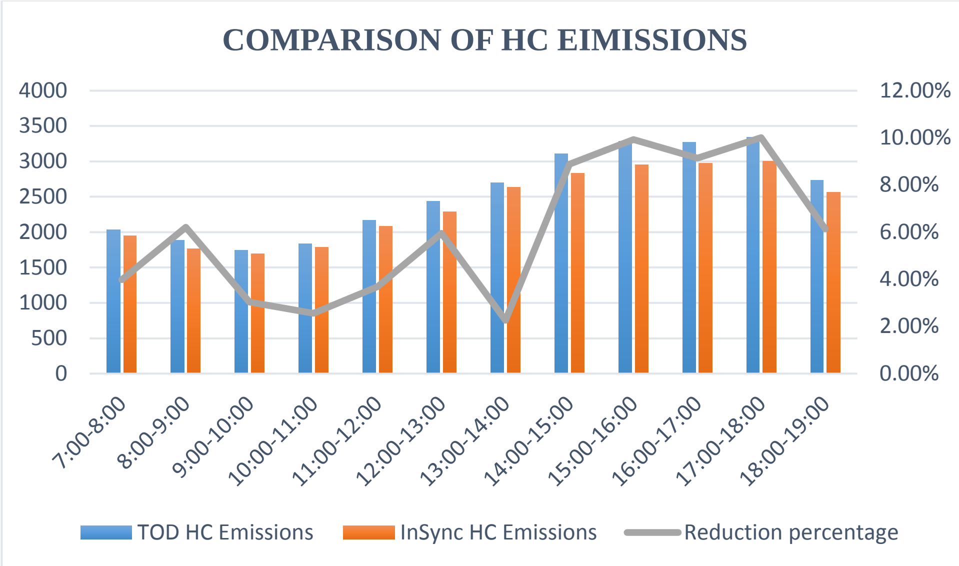

Figure 4-9. Comparison of HC emissions

From Figure 4-7, the comparison of HC emissions between the two signal control systems shows the trend of the HC emissions of both systems. It shows all decrease from 7:00 to 10:00, then increase from 10:00 to 18:00 hour by hour, and then decrease from 18:00 to 19:00. That is the emission quantity based on the fuel consumption and traffic volume. The curve of reduction percentage also shows similar tendency except there is a drop on 13:00 to 14:00. Basically, the reduction of InSync HC emissions is changed by the changes of traffic volume, the reduction lessens when the traffic volume increase and this rate gets less when there is less traffic in the corridor. Simply explained it can be illustrated that when there is congestion the reduction of emission might be significant due to the operation of ATCS, and when there is lesser traffic the emission of the ATCS might be as same as the TOD plan.

Figures 4-8 and 4-9 show a comparison of CO and NOx emissions of the two systems. The trend of reduction percentage shows a similar tendency of emissions hour by hour as well. The percentage trend from 13:00- 14:00 is also a drop in these two kinds of pollutants. It can be concluded that the methodology may have some errors but the results are still within the statistical margin of error.

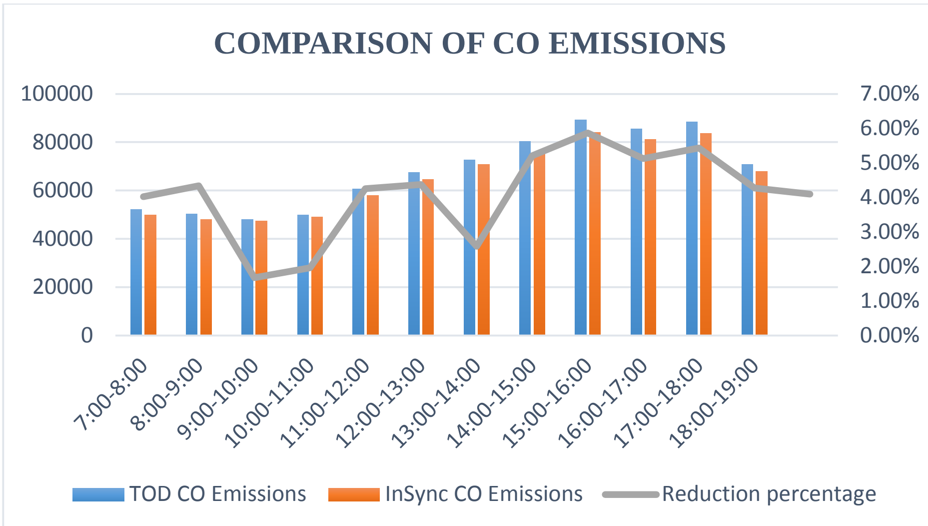

Figure 4-10. Comparison of CO emissions

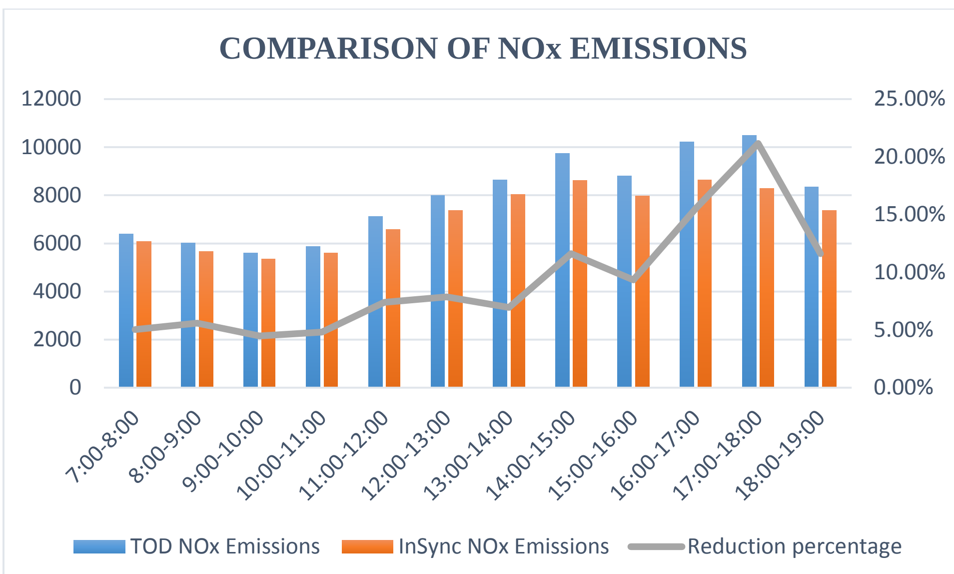

Figure 4-11. Comparison of NOx emissions

Because these two samples were before-and-after observations on the same subjects, paired t-tests can be used to compare the statistical significance of the change in emissions of the two systems.

Let x represent the emissions data before the installing of ATCS, which is TOD Plans; let y represent the emissions data after the installing of ATCS that is InSync Plans. To test the null hypothesis that the true mean difference is zero, the procedure is as follows:

Calculate the difference $(d_i = y_i - x_i)$ between the two observations on each pair, so in this research, the differences is negative differences. Calculate the mean difference, $\bar{d}$. Calculate the standard deviation of the differences, s_d, and use this to calculate the standard error of the mean difference, $SE(\bar{d}) = \frac{s_d}{\sqrt{n}}$. Calculate the t-statistic, which is given by $= \frac{\bar{d}.}{SE(\bar{d})}$. Under the null hypothesis, this statistic follows a t-distribution with $n - 1$ degrees of freedom. Use tables of the t-distribution to compare your value for T to the t_{n-1} distribution. This will give the p-value for the paired t-test.

In this research the SPSS was used to carry out the paired t-test results, the HC emission results comparison shows as Figure 4-10. 12 pairs was listed between TOD and InSync Plans and each pair contains 5 multiple times simulation, the detailed data which import to SPSS was given in Appendix A.

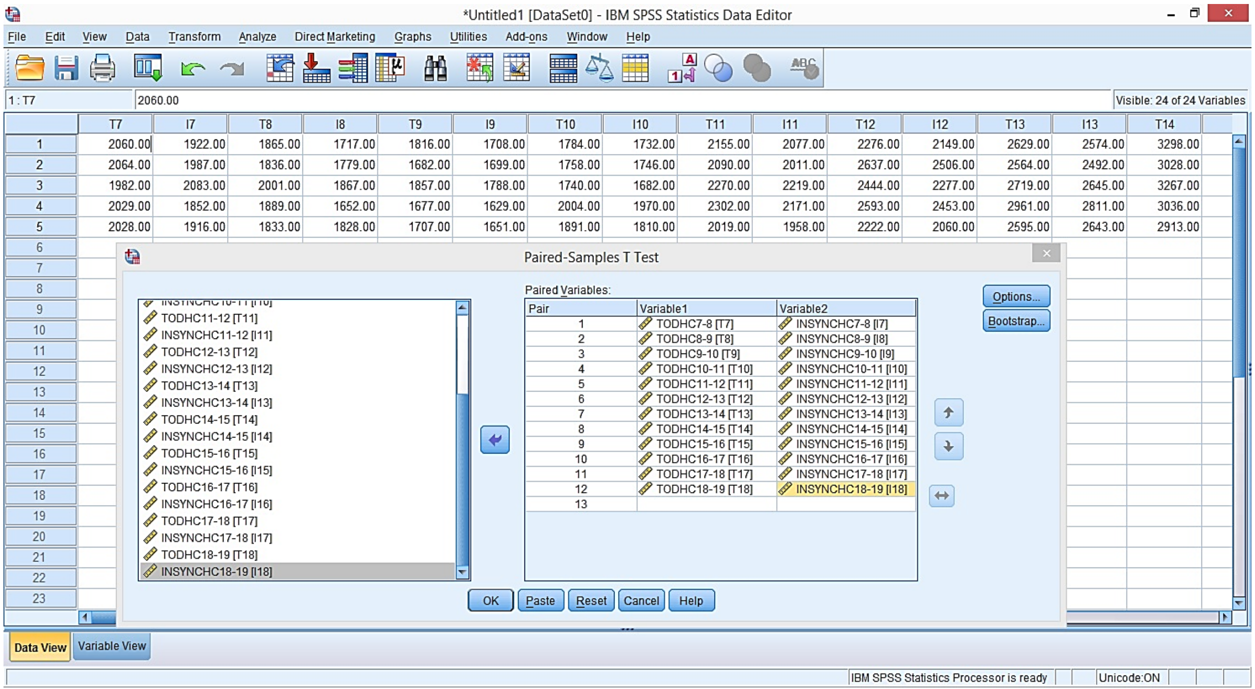

Figure 4-12. SPSS interface of paired t-test of HC emission results

For all the three emissions, the paired t-test results shows are shown in tables 4-15:

Table 4-15. The average paired t-test result of all the three emissions

	95% Confidence Interval of the Difference		t	df	Sig. (2-tailed)
	Lower	Upper			
HC emissions	79.93	251.06	6.40	4	.037
CO emissions	1806.80	4043.45	13.12	4	.017
NOx emissions	468.08	1144.34	10.12	4	.019

For HC emissions, from the observation of these paired t statistic, average t = 6.40, and p = 0.037, the null hypothesis is rejected, since p < 0.05. This test shows that there is strong statistical evidence that the InSync installation improves traffic emissions. If this experiment was repeated 100 times, 95 times the true value for the difference would lie in the 95% confidence interval. This is why it is important to look at the 95% Confidence Interval (95% CI). In this data set, the 95% CI is from 79.93 to 251.06. This confirms that, although the difference in emission reductions is statistically significant, it is actually relatively small.

For CO emissions, from the observation of these paired t statistic, average t = 13.12, and p = 0.017, the null hypothesis is rejected, since $p < 0.05$. There is also strong evidence that the InSync installation improves traffic emissions. In this data set, the 95% CI is from 1806.80 to 4043.45, this difference in emission reductions is statistically significant.

For NOx emissions, from the last row observation of these paired t statistic, average t = 10.12, and p = 0.019, the null hypothesis is rejected, since $p < 0.05$. There is also strong evidence that the InSync installation improves traffic emissions. In this data set, the 95% CI is from 468.08 to 1144.34, this difference in emission reductions is statistically significant.

4.6 SUMMARY OF EMISSIONS TESTING

As all the charts show above, the three kinds of pollutants have been estimated to be reduced by the operating of the InSync System. Generally, in consideration of the limitation of both the microsimulation model and the data source's accuracy, the emission benefits for the InSync system is obviously significant. In addition, from the SPSS paired t-test analysis, the difference in before and after comparison is practically important, not just statistically significant.

5.0 LINKING MIRCOSIMULATION AND OTHER MODELS

The methodology developed and tested predicted overall emission levels generated by the line emission source of a roadway corridor, but other models are needed to estimate pollutant levels at sensitive receptors. Using more accurate emission models and a dispersion model will provide this information that can then be compared to acceptable pollutant levels. Based upon a review of current methods used for emissions and dispersion this expansion of the methodology developed is suggested as follows.

5.1 PROPOSED MODELS

5.1.1 Emission Models

MOVES (Motor Vehicle Emission Simulator) is one type of emission model that has been used for simulating emission levels of traffic intersections [14]. EPA's (Environmental Protection Agency) Office of Transportation and Air Quality (OTAQ) developed the Motor Vehicle Emission Simulator (MOVES) model. This model is the accepted methodology by the FHWA (Federal Highway Administration) to determine the environmental emission impacts of highway projects. This emission modeling system estimates emissions for mobile sources covering a broad range of pollutants and allows multiple scale analysis.

Comprehensive Modal Emissions Model (CMEM) [15], a research project that began on 1995, and was developed by the College of Engineering-Center for Environmental Research and Technology (CECERT) at the University of California-Riverside and sponsored by the National Cooperative Highway Research Program. The overall objective of this research project was to develop and verify a modal emissions model that accurately reflects Light-Duty Vehicle (LDV, i.e., cars and small trucks) emissions produced as a function of the vehicle's operating mode. The model is comprehensive in the sense that it is able to predict emissions for a wide variety of LDVs in various states of condition (e.g., properly functioning, deteriorated, malfunctioning). The model is capable of predicting second-by-second tailpipe (and engine-out) emissions and fuel consumption for a wide range of vehicle/technology categories.

5.1.2 Dispersion Models

Dispersion modeling uses mathematical formulations to characterize the atmospheric processes that disperse a pollutant emitted by a source. Atmospheric dispersion models are computer programs that use mathematical algorithms to simulate how pollutants in the ambient atmosphere disperse and how they react in the atmosphere. Based on emissions and meteorological inputs, dispersion models can be used to predict concentrations at selected downwind receptor locations. Following are the preferred and recommended models developed by or accepted for use by the U.S. Environmental Protection Agency (U.S. EPA):

AERMOD is an atmospheric dispersion model based on atmospheric boundary layer turbulence structure and scaling concepts, including treatment of multiple ground level and elevated point, area and volume sources. It handles flat or complex, rural or urban terrain and includes algorithms for building effects and plume penetration of inversions aloft. It uses Gaussian dispersion for stable atmospheric conditions (i.e., low turbulence) and non-Gaussian dispersion for unstable conditions (high turbulence). Algorithms for plume depletion by wet and dry deposition are also included in the model. This model was in development for approximately 14 years before being officially accepted by the U.S. EPA.

CALINE4 [7] is a steady-state Gaussian dispersion model designed to determine pollution concentrations at receptor locations downwind of highways located in relatively uncomplicated terrain. CALINE4 can be used to predict roadside concentrations of carbon monoxide, nitrogen oxides and particulate matters. Although CALINE4 is not considered suitable for predicting pollutant dispersion in street canyon, it has been used for concentration estimation near intersection or highway.

CAL3QHC is a CALINE3 based model with queuing calculations and a traffic model to calculate delays and queues that occur at signalized intersections. CAL3QHCR is a more refined version based on CAL3QHC that requires local meteorological data. CAL3QHC model is mainly used for signal-controlled intersections, for it has additional methods to estimate queue lengths and emissions from idling vehicles. CAL3QHC can be used for estimation of PM and CO concentrations near signal-controlled intersections, and model comparison studies have shown its capability in estimating PM and CO concentrations near intersection or traffic flow.

5.2 METHODOLOGY OF LINKING MODELS

To estimate the impacts of transportation systems on air quality, a comprehensive platform of air quality criteria pollutant levels and data sources from government agencies, land use planners, environmental professionals and traffic designers is needed. These data sources use emission computer models to estimate concentrations of pollutants that will be generated by transportation systems. To estimate more accurate emission data will need emission models, which can use vehicle trajectory generated from microsimulation models; To estimate pollutant levels at a specific geographic location will need dispersion models, which can use both traffic variables and emission factors generated from microsimulation and emission models, thus linking these models can be critical to comprehensive analysis the air quality benefits of ATCS operation. This is shown in Figure 5-1.

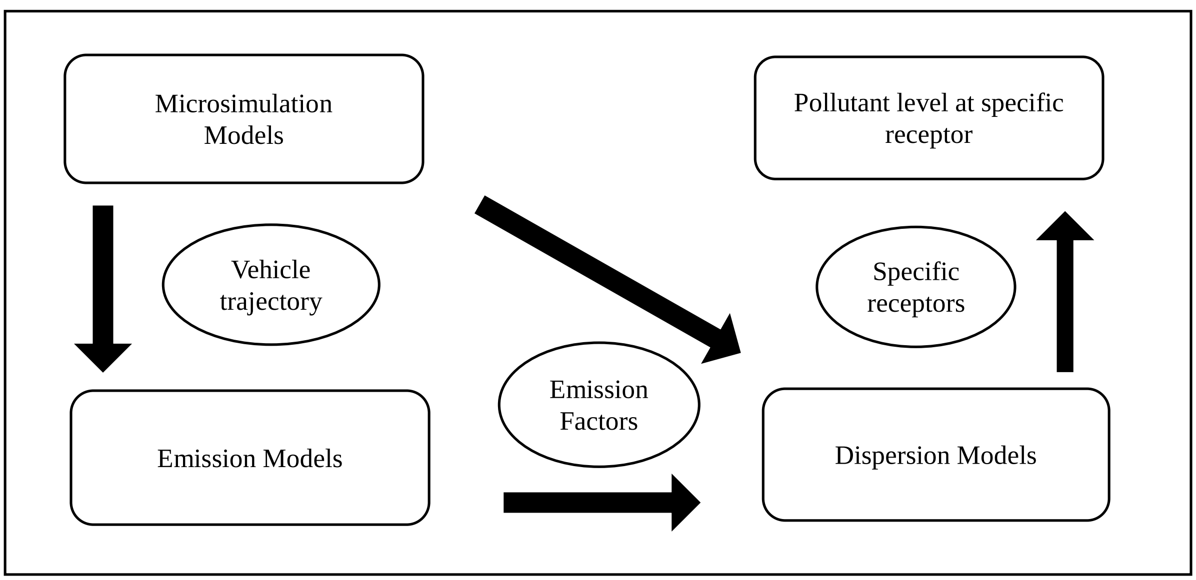

Figure 5-1. Flow-chart of the linking models methodology

5.3 MIRCOSINULATION MODELS AND EMISSION MODELS

5.3.1 Emission data elements

Emissions data in the air quality modeling process are divided into six source categories which includes Point Source Emissions Data; On-Road Mobile Source Emissions Data; Area Source Emissions Data, etc. On-road mobile source emission data is the primary research objective of the traffic emission evaluation and analysis. [14]

On-road mobile source emission inventories are typically based on vehicle miles traveled (VMT) estimates that are output from local travel demand models for various roadway segments or "links." Hourly VMT estimates for each link are multiplied by emission rates can be calculated with emission model. Emission rates are developed separately for freeway and arterial links and matched to the hourly VMT based on average hourly operating speed. The vehicle characteristics can also be presented by showing age and speed distribution which generated by microsimulation models.

5.3.2 Linking between Microsimulation and Emission Models

Estimating vehicle emissions based on second-by-second vehicle operation encourages the integration of microscopic traffic simulation models with more accurate vehicle activity-based regional mobile emissions models. The linking between Microsimulation and Emission Models can be made because the microsimulation models can generate the data for Emission Models utilization. There are many connections between the two kinds of models and some of them can be paired during analyzing due to their parameter commonality. The following table shows some pairings of the microsimulation and emission model software.

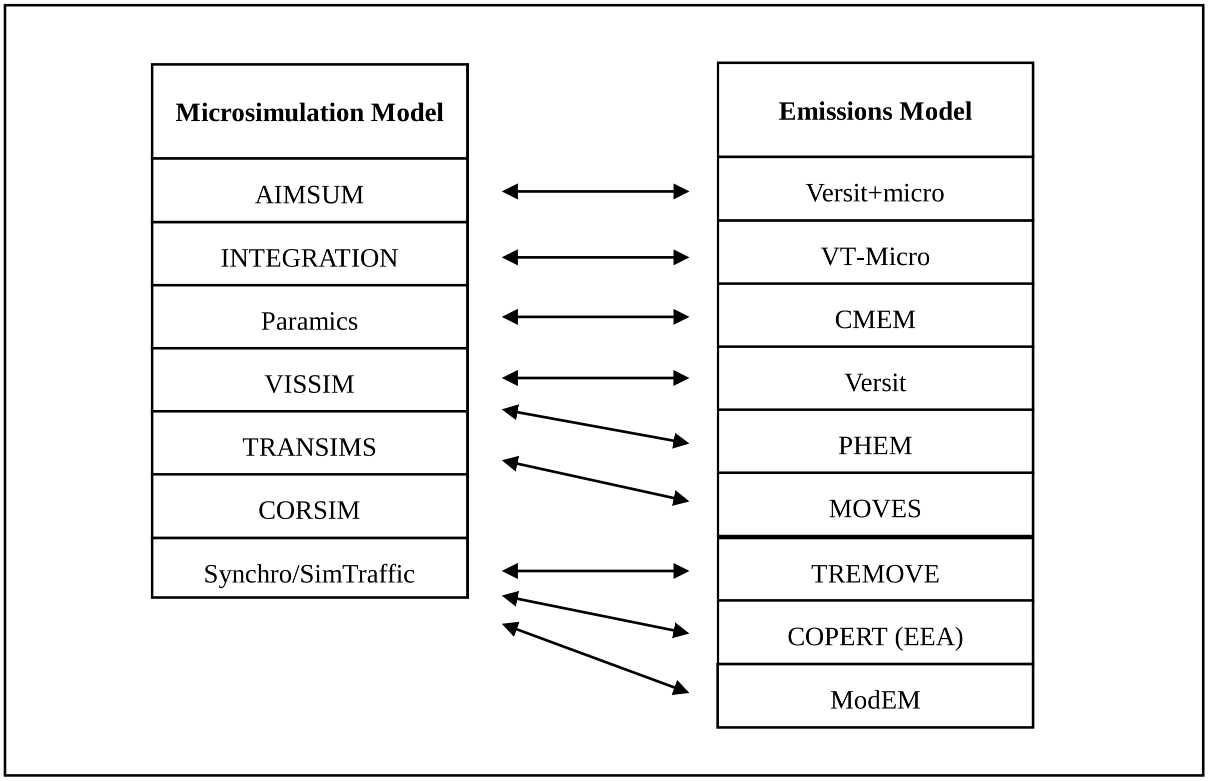

Figure 5-2. Microsimulation – Emissions Modeling Pairings [16]

Microsimulation models have been seen as the first step for the transportation and emission modeling integration analysis. One of the key attributes of the microsimulation model is its open architecture which enables the integration of plug-in modules for carrying out specific functions. [14] This is performed through "Application Programming Interfaces" or APIs. There are many add-in or plug-in emission modules in traffic simulation models. For instance, as the table shows above, the Paramics CMEM plugin provides an interface between CMEM and Paramics. The integrating CMEM within PARAMICS was accomplished by creating an API through the use of the Paramics Programmer utility.

There are also some particular software for linking the microsimulation and emission models. [17] For example, VIMIS is custom software developed to integrate between VISSIM and MOVES to automate the design of experiment portion and facilitate the conversion process of VISSIM files into MOVES files.

5.3.3 Linking between Synchro and MOVE2014

Synchro can be integrated with many emission models by applying different methodologies. Based upon a review of the available emission models it is recommended that in order to provide more accurate and specific emission information linking the Synchro model with MOVE2014 is recommended. It has been determined that the following is a description of how the combination of Synchro and MOVE2014 and can be applied in concept to expand upon the methodology developed as part of this research.

The MOVE2014 model includes a default database that summarizes emissions relevant information for the entire United States which is updated continually. However, for many uses, up-to-date local inputs and simulation results will be more appropriate.

As discussed earlier, the output from the Synchro model can be used as input into the MOVE2014 model. For MOVE2014, the first input step is to create a project-level database where imported data are stored. Input files include meteorology data, traffic composition and percentage of trucks, length, volume, average speeds and grade, distribution of vehicles age, operating mode distribution for running emissions, link drive schedules, and fuel information (gasoline, diesel). A summary of MOVES example project-level parameters can be seen in Table 5.1. This illustrates the greater details that MOVES uses to estimate emission as compared to the emission estimating method used by Synchro.

Table 5-1. Summary of example project-level parameters [14]

PARAMETERs	**Examples**
Location county	Allegheny Country, Pennsylvania
Calendar year	2014
Month	September
Time	8:00 am -9:00 am
Weekday/weekend	Weekday
Temperature	72 F
Humidity	70.0%
Roadway type	Urban restricted access—represents freeway urban road with three lanes in each direction
Types of vehicles	60% Passenger cars–LDGV, 37% passenger trucks–LDGT, and 3% long-haul combination diesel trucks–HDDV
Type of fuel	Gasoline for passenger cars (LDGV) and trucks (LDGT); diesel for heavy-duty diesel trucks (HDDV)
Roadway length	Approx. 1 mile/link – Total of 10 miles
Link traffic volume	6,500 vehicles per hour
Link truck traffic	3% Heavy-duty diesel trucks (HDDV)
Average road grade	0%
Link average speed	20–40 miles per hour
Pollutant process	Running exhaust emissions
Output	Output CO, NOx, PM2.5, PM10, and atmospheric CO2

In the MOVE2014 modeling process, the user specifies vehicle types, time periods, geographical areas, pollutants, vehicle operating characteristics, and road types will be modeled. The model then will perform a series of calculations, which have been carefully developed to accurately reflect vehicle operating processes, such as cold start or extended idle, and provide estimates of bulk emissions or emission rates as the results.

5.4 MIRCORSIMULATION, EMISSION AND DISPERSION MODELS

5.4.1 Determinants of pollutants impact

Observed meteorological data for use in air quality modeling consist of physical parameters that are measured directly by instrumentation, and include temperature, dew point, wind direction, wind speed, cloud cover, cloud layer(s), ceiling height, visibility, current weather, and precipitation amount. These data are used in air quality models to capture the atmospheric conditions occurring at a source and/or receptor location, and therefore, play an important role as they effect the concentration of pollutants at receptors of interest.

Line source dispersion models are easily affected much by some very parameters like wind speed, the pollutants impact can various a lot since the changing wind condition. As results, the field measurements data are critical for the analyzing of Dispersion Models in varied locations and time periods beyond the vehicles trajectory data from microsimulation models

5.4.2 Linking between Synchro, MOVE2014 and CAL3QHC Models

The combination between MOVE2014 and CAL3QHC was discussed in the following part and can be applied in the future research based on the principle.

The primary input parameters for CAL3QHC include emission factor, [7] traffic parameters, meteorological parameters and site position. The traffic parameters which can generated from microsimulation model Synchro are traffic volume, traffic signal type, and saturation flow rate, etc. The vehicle types are also the principal factors which conclude light-duty diesel vehicles (LDDV), heavy-duty diesel vehicles (HDDV), light-duty 13 gasoline vehicles (LDGV) and heavy-duty diesel vehicles (HDGV). The counting data should be separate for those four scenarios and will be used in the CAL3QHC Model application part. The emission factors can generated from emission model MOVE2014 include composite running emission factor and idle emission factor.

The receptors site position can be determined according to specific sensitive air quality receptor sites which include commercial, school, church, residential land uses in the corridor.

The meteorological parameters such as the wind speed and mixing height are the key factor to determine the performance of models for the pollutants concentrations such as $PM_{2.5}$ and CO, etc. Future research should be applied in the measurements validating and modeling of the Dispersion Model.

6.0 SUMMARY AND CONCLUSIONS

This section summaries the comparison of results, determines whether the results match the hypothesis, and states the viewpoint on the future research.

6.1 SUMMARY OF ENVIRONMENTAL BENEFITS

The objective of this research was to develop a methodology to investigate how much an ATCS deployment reduces vehicular emissions generated by traffic in a signalized corridor network. The research described modelling the microsimulation model using Synchro to simulate the vehicle trajectory of two signal plans, InSync Plans and TOD Plans, based on the actual counting data and representative timing data imputing resulting in a comparison of the emission results. This methodology was tested by applying it to an operating ATCS system.

As the results showed, all of the three pollutants (HC, CO and NOx) have been estimated to be reduced by the operating of InSync System when applied to a specific test corridor. Specifically, InSync Plans outperforms TOD Plans in environmental performance measures by saving 5.98% in HC emissions, 4.09% in CO emissions and 9.28% in NOx emissions during a twelve hour test period. Although moderate, these improvements, especially NOx emissions, are statistically significant from the SPSS paired t-test analysis.

6.2 SUMMARY OF LINKING MODELS

The linking between microsimulation models, emission models and dispersion models was explored and it was concluded that this expansion of the methodology could comprehensively evaluate the emission benefits at specific receptors.

6.3 FUTURE RESEARCH

Future research should be emphasized in following 3 aspects:

Modelling Accuracy: the calibration and validation of the Synchro model in this research was not determined, there were many assumptions and limitations. To develop a more accurate model for simulation is critical to calibrate and validate the model based on field data with the ATCS operating.

Representative Data Accuracy: this research uses the aggregation method to generate the representative timing data. There needs to be other methods that can be applied by modeling the operations for individual cycles and inputting them to microsimulation models. Future research should be focus on this area to fully represent the actual performance of the ATCS.

Linking between Microsimulation Models and other Models: this research was not sufficient to complete all the integration methods between microsimulation and other emission and dispersion models, but provides a conceptual methodology of linking microsimulation models with emission and dispersion models, which should be applied into real case operations and calculations to estimate benefits as specific receptors.

APPENDIX A

In this section, all of three emission results are presented for the 12-hour simulation in TOD and InSync Plans.

HC Emissions for 12-hour simulation in TOD and InSync Plans

Time	Multiple Run No.	HC Emissions (g)		Time	Multiple Run No.	HC Emissions (g)	
		TOD	InSync			TOD	InSync
7:00-8:00	1	2,060	1,922	**13:00-14:00**	1	2,629	2,574
	2	2,064	1,987		2	2,564	2,492
	3	1,982	2,083		3	2,719	2,645
	4	2,029	1,852		4	2,961	2,811
	5	2,028	1,916		5	2,595	2,643
	Avg	2,033	1,952		Avg	2,694	2,633
8:00-9:00	1	1,865	1,717	**14:00-15:00**	1	3,298	3,014
	2	1,836	1,779		2	3,028	2,749
	3	2,001	1,867		3	3,267	2,811
	4	1,889	1,652		4	3,036	2,840
	5	1,833	1,828		5	2,913	2,746
	Avg	1,885	1,768		Avg	3,108	2,832
9:00-10:00	1	1,816	1,708	**15:00-16:00**	1	3,109	2,744
	2	1,682	1,699		2	3,383	3,074
	3	1,857	1,788		3	3,640	3,284
	4	1,677	1,629		4	3,282	2,911
	5	1,707	1,651		5	2,994	2,767
	Avg	1,748	1,695		Avg	3,282	2,956
10:00-11:00	1	1,784	1,732	**16:00-17:00**	1	3,183	2,874
	2	1,758	1,746		2	3,320	3,207
	3	1,740	1,682		3	3,211	2,905
	4	2,004	1,970		4	3,389	2,951
	5	1,891	1,810		5	3,251	2,923
	Avg	1,835	1,788		Avg	3,271	2,972
11:00-12:00	1	2,155	2,077	**17:00-18:00**	1	3,289	2,966
	2	2,090	2,011		2	3,362	3,091
	3	2,270	2,219		3	3,405	2,996
	4	2,302	2,171		4	3,400	3,018
	5	2,019	1,958		5	3,229	2,944
	Avg	2,167	2,087		Avg	3,337	3,003
12:00-13:00	1	2,276	2,149	**18:00-19:00**	1	2,716	2,457
	2	2,637	2,506		2	2,782	2,730
	3	2,444	2,277		3	2,771	2,672
	4	2,593	2,453		4	2,819	2,590
	5	2,222	2,060		5	2,588	2,386
	Avg	2,434	2,289		Avg	2,735	2,567

CO Emissions for 12-hour simulation in TOD and InSync Plans

Time	Multiple Run No.	CO Emissions (g)		Time	Multiple Run No.	CO Emissions (g)	
		TOD	InSync			TOD	InSync
7:00-8:00	1	52,615	49,737	**13:00-14:00**	1	71,706	70,002
	2	52,621	50,902		2	70,625	68,693
	3	51,216	52,100		3	73,122	71,058
	4	52,665	48,329		4	77,048	74,926
	5	51,397	48,981		5	70,828	69,259
	Avg	52,103	50,010		Avg	72,666	70,788
8:00-9:00	1	50,087	46,948	**14:00-15:00**	1	84,057	79,155
	2	49,842	48,419		2	78,854	74,529
	3	52,169	49,768		3	83,629	79,317
	4	50,208	46,207		4	79,268	75,013
	5	48,749	48,815		5	75,610	72,506
	Avg	50,211	48,032		Avg	80,283	76,104
9:00-10:00	1	49,611	48,656	**15:00-16:00**	1	86,921	81,688
	2	46,881	46,871		2	91,070	84,183
	3	49,657	48,015		3	94,711	88,409
	4	46,737	46,530		4	88,288	84,715
	5	47,762	46,548		5	85,343	81,159
	Avg	48,130	47,324		Avg	89,266	84,031
10:00-11:00	1	48,823	47,872	**16:00-17:00**	1	83,500	79,005
	2	48,750	47,536		2	87,393	82,847
	3	48,531	48,546		3	84,058	79,966
	4	52,578	50,864		4	86,998	82,618
	5	51,044	50,017		5	85,460	81,049
	Avg	49,945	48,967		Avg	85,482	81,097
11:00-12:00	1	60,084	57,104	**17:00-18:00**	1	86,896	82,548
	2	59,684	57,651		2	89,397	84,960
	3	62,196	59,674		3	89,677	84,219
	4	62,969	60,186		4	89,554	84,803
	5	58,078	55,496		5	86,577	81,565
	Avg	60,602	58,022		Avg	88,420	83,619
12:00-13:00	1	64,559	62,844	**18:00-19:00**	1	70,955	68,469
	2	71,123	65,838		2	72,017	67,291
	3	68,272	65,318		3	71,190	69,573
	4	69,973	68,057		4	72,427	70,190
	5	63,957	61,049		5	67,900	63,816
	Avg	67,577	64,621		Avg	70,898	67,868

NOx Emissions for 12-hour simulation in TOD and InSync Plans

Time	Multiple Run No.	NOx Emissions (g)		Time	Multiple Run No.	NOx Emissions (g)	
		TOD	InSync			TOD	InSync
7:00-8:00	1	6,491	6,041	**13:00-14:00**	1	8,459	7,716
	2	6,505	6,173		2	8,239	7,914
	3	6,250	6,348		3	8,758	8,017
	4	6,442	5,812		4	9,309	8,563
	5	6,307	6,006		5	8,366	7,915
	Avg	6,399	6,076		Avg	8,626	8,025
8:00-9:00	1	5,975	5,598	**14:00-15:00**	1	10,146	8,815
	2	5,894	5,706		2	9,517	8,742
	3	6,320	5,922		3	10,248	9,057
	4	6,024	5,343		4	9,523	8,394
	5	5,873	5,837		5	9,272	8,040
	Avg	6,017	5,681		Avg	9,741	8,610
9:00-10:00	1	5,758	5,527	**15:00-16:00**	1	8,483	8,659
	2	5,432	5,195		2	9,304	8,913
	3	5,862	5,601		3	9,313	7,368
	4	5,441	5,196		4	8,585	7,810
	5	5,530	5,249		5	8,334	7,159
	Avg	5,605	5,354		Avg	8,804	7,982
10:00-11:00	1	5,716	5,421	**16:00-17:00**	1	9,850	8,508
	2	5,712	5,514		2	10,397	8,417
	3	5,674	5,488		3	10,052	8,504
	4	6,281	5,889		4	10,515	9,027
	5	6,018	5,672		5	10,274	8,706
	Avg	5,880	5,597		Avg	10,218	8,632
11:00-12:00	1	7,057	6,576	**17:00-18:00**	1	10,396	8,045
	2	6,912	6,393		2	10,575	8,451
	3	7,328	6,628		3	10,528	8,112
	4	7,434	6,817		4	10,666	8,689
	5	6,797	6,492		5	10,315	8,089
	Avg	7,106	6,581		Avg	10,496	8,277
12:00-13:00	1	7,559	7,205	**18:00-19:00**	1	8,278	7,748
	2	8,527	7,309		2	8,431	7,624
	3	8,103	7,539		3	8,514	7,064
	4	8,354	7,291		4	8,690	7,545
	5	7,410	7,467		5	7,808	6,892
	Avg	7,991	7,362		Avg	8,344	7,375

APPENDIX B

In this section, all of three emissions' paired t-test results are presented for the 12-hour simulation in TOD and InSync Plans from SPSS.

For HC emissions, the paired t-test results shows are shown in following tables:

Paired Samples Statistics for HC emissions

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	TODHC7-8	2032.6000	5	32.90593	14.71598
	INSYNCHC7-8	1952.0000	5	87.43855	39.10371
Pair 2	TODHC8-9	1884.8000	5	68.87815	30.80325
	INSYNCHC8-9	1768.6000	5	85.99012	38.45595
Pair 3	TODHC9-10	1747.8000	5	83.04035	37.13677
	INSYNCHC9-10	1695.0000	5	61.49390	27.50091
Pair 4	TODHC10-11	1835.4000	5	110.96306	49.62419
	INSYNCHC10-11	1788.0000	5	111.51681	49.87184
Pair 5	TODHC11-12	2167.2000	5	119.17508	53.29672
	INSYNCHC11-12	2087.2000	5	108.39373	48.47515
Pair 6	TODHC12-13	2434.4000	5	184.72764	82.61271
	INSYNCHC12-13	2289.0000	5	191.16093	85.48977
Pair 7	TODHC13-14	2693.6000	5	160.34276	71.70746
	INSYNCHC13-14	2633.0000	5	117.56913	52.57851
Pair 8	TODHC14-15	3108.4000	5	166.57521	74.49470
	INSYNCHC14-15	2832.0000	5	109.44633	48.94589
Pair 9	TODHC15-16	3281.6000	5	250.61784	112.07970
	INSYNCHC15-16	2956.0000	5	225.94136	101.04405
Pair 10	TODHC16-17	3270.8000	5	83.76873	37.46251
	INSYNCHC16-17	2972.0000	5	134.31307	60.06663
Pair 11	TODHC17-18	3337.0000	5	76.13475	34.04849
	INSYNCHC17-18	3003.0000	5	56.71860	25.36533
Pair 12	TODHC18-19	2735.2000	5	90.18148	40.33039
	INSYNCHC18-19	2567.0000	5	144.03472	64.41428

Paired Samples Correlations for HC emissions

		N	Correlation	Sig.
Pair 1	TODHC7-8 & INSYNCHC7-8	5	-.506	.384
Pair 2	TODHC8-9 & INSYNCHC8-9	5	.354	.559
Pair 3	TODHC9-10 & INSYNCHC9-10	5	.844	.072
Pair 4	TODHC10-11 & INSYNCHC10-11	5	.973	.005
Pair 5	TODHC11-12 & INSYNCHC11-12	5	.968	.007
Pair 6	TODHC12-13 & INSYNCHC12-13	5	.996	.000
Pair 7	TODHC13-14 & INSYNCHC13-14	5	.915	.029
Pair 8	TODHC14-15 & INSYNCHC14-15	5	.742	.151
Pair 9	TODHC15-16 & INSYNCHC15-16	5	.973	.005
Pair 10	TODHC16-17 & INSYNCHC16-17	5	.504	.387
Pair 11	TODHC17-18 & INSYNCHC17-18	5	.626	.258
Pair 12	TODHC18-19 & INSYNCHC18-19	5	.810	.097

Paired Samples Test results for HC emissions

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	TODHC7-8 - INSYNCHC7-8	80.60000	107.89486	48.25205	-53.36916	214.56916	1.670	4	.170
Pair 2	TODHC8-9 - INSYNCHC8-9	116.20000	89.14987	39.86904	5.50581	226.89419	2.915	4	.043
Pair 3	TODHC9-10 - INSYNCHC9-10	52.80000	45.31777	20.26672	-3.46944	109.06944	2.605	4	.060
Pair 4	TODHC10-11 - INSYNCHC10-11	47.40000	25.95766	11.60862	15.16931	79.63069	4.083	4	.015
Pair 5	TODHC11-12 - INSYNCHC11-12	80.00000	30.85450	13.79855	41.68908	118.31092	5.798	4	.004
Pair 6	TODHC12-13 - INSYNCHC12-13	145.40000	18.14663	8.11542	122.86799	167.93201	17.917	4	.000
Pair 7	TODHC13-14 - INSYNCHC13-14	60.60000	70.93518	31.72318	-27.47766	148.67766	1.910	4	.129
Pair 8	TODHC14-15 - INSYNCHC14-15	276.40000	112.64235	50.37519	136.53604	416.26396	5.487	4	.005
Pair 9	TODHC15-16 - INSYNCHC15-16	325.60000	60.28101	26.95849	250.75124	400.44876	12.078	4	.000
Pair 10	TODHC16-17 - INSYNCHC16-17	298.80000	117.16100	52.39599	153.32540	444.27460	5.703	4	.005
Pair 11	TODHC17-18 - INSYNCHC17-18	334.00000	60.04165	26.85144	259.44844	408.55156	12.439	4	.000
Pair 12	TODHC18-19 - INSYNCHC18-19	168.20000	88.56467	39.60732	58.23244	278.16756	4.247	4	.013
Avg					79.9341	251.06587	6.404		.037

For CO emissions, the paired t-test results shows as below:

Paired Samples Statistics for CO emissions

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	TODCO7-8	52102.8000	5	729.98575	326.45955
	INSYNCCO7-8	50009.8000	5	1510.20651	675.38488
Pair 2	TODCO8-9	50211.0000	5	1237.20997	553.29712
	INSYNCCO8-9	48031.4000	5	1438.94347	643.51508
Pair 3	TODCO9-10	48129.6000	5	1428.36998	638.78647
	INSYNCCO9-10	47324.0000	5	960.40694	429.50704
Pair 4	TODCO10-11	49945.2000	5	1790.72575	800.83690
	INSYNCCO10-11	48967.0000	5	1425.23121	637.38277
Pair 5	TODCO11-12	60602.2000	5	1976.43295	883.88769
	INSYNCCO11-12	58022.2000	5	1921.78568	859.44868
Pair 6	TODCO12-13	67576.8000	5	3201.97911	1431.96859
	INSYNCCO12-13	64621.2000	5	2724.42227	1218.39868
Pair 7	TODCO13-14	72665.8000	5	2639.85723	1180.58004
	INSYNCCO13-14	70787.6000	5	2476.92376	1107.71398
Pair 8	TODCO14-15	80283.6000	5	3547.81571	1586.63142
	INSYNCCO14-15	76104.0000	5	3010.33553	1346.26298
Pair 9	TODCO15-16	89266.6000	5	3699.59042	1654.50714
	INSYNCCO15-16	84030.8000	5	2889.45829	1292.20503
Pair 10	TODCO16-17	85481.8000	5	1725.30873	771.58152
	INSYNCCO16-17	81097.0000	5	1660.86348	742.76073
Pair 11	TODCO17-18	88420.2000	5	1544.32500	690.64314
	INSYNCCO17-18	83619.0000	5	1493.82847	668.06040
Pair 12	TODCO18-19	70897.8000	5	1779.50266	795.81778
	INSYNCCO18-19	67867.8000	5	2520.49315	1127.19880

Paired Samples Correlations for CO emissions

		N	Correlation	Sig.
Pair 1	TODCO7-8 & INSYNCCO7-8	5	-.397	.508
Pair 2	TODCO8-9 & INSYNCCO8-9	5	.316	.604
Pair 3	TODCO9-10 & INSYNCCO9-10	5	.909	.033
Pair 4	TODCO10-11 & INSYNCCO10-11	5	.948	.014
Pair 5	TODCO11-12 & INSYNCCO11-12	5	.984	.002
Pair 6	TODCO12-13 & INSYNCCO12-13	5	.898	.039
Pair 7	TODCO13-14 & INSYNCCO13-14	5	.998	.000
Pair 8	TODCO14-15 & INSYNCCO14-15	5	.993	.001
Pair 9	TODCO15-16 & INSYNCCO15-16	5	.940	.017
Pair 10	TODCO16-17 & INSYNCCO16-17	5	.995	.000
Pair 11	TODCO17-18 & INSYNCCO17-18	5	.956	.011
Pair 12	TODCO18-19 & INSYNCCO18-19	5	.869	.056

Paired Samples Test results for CO emissions

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	TODCO7-8 - INSYNCCO7-8	2093.00000	1920.54732	858.89487	-291.67446	4477.67446	2.437	4	.071
Pair 2	TODCO8-9 - INSYNCCO8-9	2179.60000	1573.38228	703.63795	225.98787	4133.21213	3.098	4	.036
Pair 3	TODCO9-10 - INSYNCCO9-10	805.60000	685.56130	306.59234	-45.63679	1656.83679	2.628	4	.058
Pair 4	TODCO10-11 - INSYNCCO10-11	978.20000	629.79576	281.65323	196.20528	1760.19472	3.473	4	.026
Pair 5	TODCO11-12 - INSYNCCO11-12	2580.00000	354.88942	158.71137	2139.34658	3020.65342	16.256	4	.000
Pair 6	TODCO12-13 - INSYNCCO12-13	2955.60000	1418.47006	634.35909	1194.33680	4716.86320	4.659	4	.010
Pair 7	TODCO13-14 - INSYNCCO13-14	1878.20000	236.01102	105.54734	1585.15362	2171.24638	17.795	4	.000
Pair 8	TODCO14-15 - INSYNCCO14-15	4179.60000	656.34084	293.52455	3364.64521	4994.55479	14.239	4	.000
Pair 9	TODCO15-16 - INSYNCCO15-16	5235.80000	1390.54295	621.86971	3509.21288	6962.38712	8.419	4	.001
Pair 10	TODCO16-17 - INSYNCCO16-17	4384.80000	176.47294	78.92110	4165.67990	4603.92010	55.559	4	.000
Pair 11	TODCO17-18 - INSYNCCO17-18	4801.20000	451.76731	202.03648	4240.25680	5362.14320	23.764	4	.000
Pair 12	TODCO18-19 - INSYNCCO18-19	3030.00000	1314.21897	587.73659	1398.18162	4661.81838	5.155	4	.007
Avg					1806.80794	4043.4587	13.123		.017

For NOx emissions, the paired t-test results shows as following tables:

Paired Samples Statistics for NOx emissions

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	TODNOx7-8	6399.0000	5	114.25191	51.09501
	INSYNCNOx7-8	6076.0000	5	199.50815	89.22275
Pair 2	TODNOx8-9	6017.2000	5	179.92137	80.46328
	INSYNCNOx8-9	5681.2000	5	225.92853	101.03831
Pair 3	TODNOx9-10	5604.6000	5	194.87637	87.15136
	INSYNCNOx9-10	5353.6000	5	195.06871	87.23738
Pair 4	TODNOx10-11	5880.2000	5	263.34426	117.77113
	INSYNCNOx10-11	5596.8000	5	187.50653	83.85547
Pair 5	TODNOx11-12	7105.6000	5	270.36327	120.91013
	INSYNCNOx11-12	6581.2000	5	159.05565	71.13185
Pair 6	TODNOx12-13	7990.6000	5	488.82338	218.60846
	INSYNCNOx12-13	7362.2000	5	136.79620	61.17712
Pair 7	TODNOx13-14	8626.2000	5	426.95749	190.94120
	INSYNCNOx13-14	8025.0000	5	319.92577	143.07516
Pair 8	TODNOx14-15	9741.2000	5	429.74841	192.18933
	INSYNCNOx14-15	8609.6000	5	397.11875	177.59690
Pair 9	TODNOx15-16	8803.8000	5	469.30342	209.87887
	INSYNCNOx15-16	7981.8000	5	776.04749	347.05899
Pair 10	TODNOx16-17	10217.6000	5	267.56551	119.65893
	INSYNCNOx16-17	8632.4000	5	244.68613	109.42696
Pair 11	TODNOx17-18	10496.0000	5	140.46886	62.81958
	INSYNCNOx17-18	8277.2000	5	281.25291	125.78013
Pair 12	TODNOx18-19	8344.2000	5	334.60305	149.63903
	INSYNCNOx18-19	7374.6000	5	374.17883	167.33786

Paired Samples Correlations for NOx emissions

		N	Correlation	Sig.
Pair 1	TODNOx7-8 & INSYNCNOx7-8	5	-.421	.480
Pair 2	TODNOx8-9 & INSYNCNOx8-9	5	.299	.625
Pair 3	TODNOx9-10 & INSYNCNOx9-10	5	.995	.000
Pair 4	TODNOx10-11 & INSYNCNOx10-11	5	.976	.005
Pair 5	TODNOx11-12 & INSYNCNOx11-12	5	.884	.047
Pair 6	TODNOx12-13 & INSYNCNOx12-13	5	-.103	.869
Pair 7	TODNOx13-14 & INSYNCNOx13-14	5	.896	.040
Pair 8	TODNOx14-15 & INSYNCNOx14-15	5	.871	.055
Pair 9	TODNOx15-16 & INSYNCNOx15-16	5	.247	.688
Pair 10	TODNOx16-17 & INSYNCNOx16-17	5	.572	.313
Pair 11	TODNOx17-18 & INSYNCNOx17-18	5	.859	.062
Pair 12	TODNOx18-19 & INSYNCNOx18-19	5	.523	.366

Paired Samples Test results for NOx emissions

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	TODNOx7-8 - INSYNCNOx7-8	323.00000	268.41386	120.03833	-10.27983	656.27983	2.691	4	.055
Pair 2	TODNOx8-9 - INSYNCNOx8-9	336.00000	243.13268	108.73224	34.11090	637.88910	3.090	4	.037
Pair 3	TODNOx9-10 - INSYNCNOx9-10	251.00000	20.19901	9.03327	225.91962	276.08038	27.786	4	.000
Pair 4	TODNOx10-11 - INSYNCNOx10-11	283.40000	90.31500	40.39010	171.25911	395.54089	7.017	4	.002
Pair 5	TODNOx11-12 - INSYNCNOx11-12	524.40000	149.54865	66.88019	338.71082	710.08918	7.841	4	.001
Pair 6	TODNOx12-13 - INSYNCNOx12-13	628.40000	520.98973	232.99369	-18.49419	1275.29419	2.697	4	.054
Pair 7	TODNOx13-14 - INSYNCNOx13-14	601.20000	199.66522	89.29300	353.28288	849.11712	6.733	4	.003
Pair 8	TODNOx14-15 - INSYNCNOx14-15	1131.60000	212.44952	95.01032	867.80908	1395.39092	11.910	4	.000
Pair 9	TODNOx15-16 - INSYNCNOx15-16	822.00000	801.51606	358.44888	-173.21364	1817.21364	2.293	4	.084
Pair 10	TODNOx16-17 - INSYNCNOx16-17	1585.20000	237.77132	106.33457	1289.96791	1880.43209	14.908	4	.000
Pair 11	TODNOx17-18 - INSYNCNOx17-18	2218.80000	175.97642	78.69905	2000.29642	2437.30358	28.193	4	.000
Pair 12	TODNOx18-19 - INSYNCNOx18-19	969.60000	347.88978	155.58104	537.63778	1401.56222	6.232	4	.003
Avg					468.08391	1144.34943	10.1159		.019

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