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Applicability of Adaptive Traffic Control Systems in Nevada's Urban Areas

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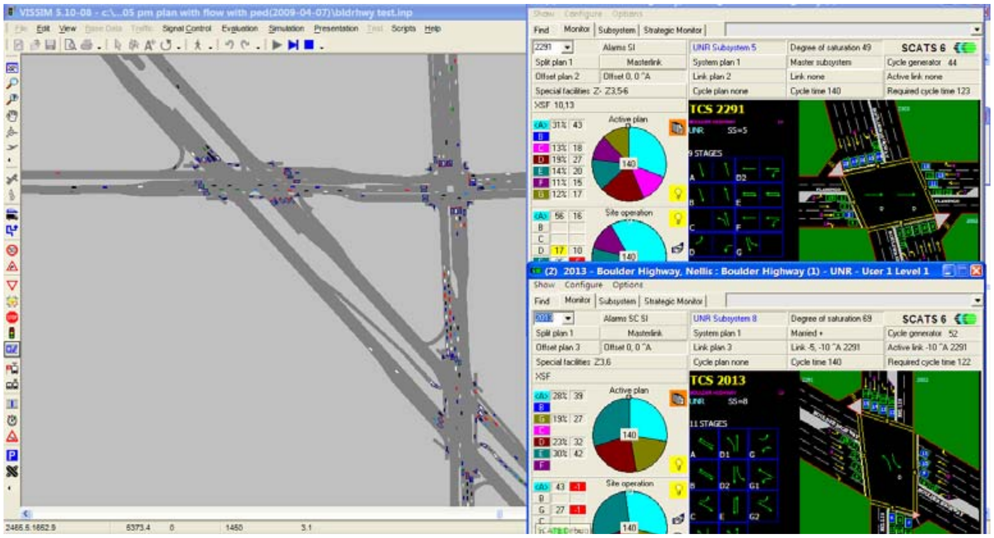
Applicability of Adaptive Traffic Control Systems in Nevada's Urban Areas

Final Report



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Executive Summary

This report documented the results of a comprehensive evaluation of Adaptive Traffic Control Systems (ATCSs). The primary goal of the study was to assess whether and how ATCSs might be applied in Las Vegas and other Nevada urbanized areas as a cost effective means of reducing traffic congestion and air pollution. Two major objectives associated with this goal were: (1) to provide a comprehensive evaluation on selected ATCSs for their operational efficiency; and (2) to develop guidelines for best implementing ATCSs in place of traditional closed-loop or centralized signal control systems. To achieve these objectives, ATCSs needed to be evaluated against actuated coordinated time-of-day (TOD) plans under a wide range of traffic flow conditions.

The project involved two major ATCSs: SCATS developed by the Roads and Traffic Authority of New South Wales, Australia; and ACS Lite developed by the Federal Highway Administration (FHWA) in partnership with Siemens ITS. Software-in-the-loop traffic simulation platforms were established which involved microscopic traffic simulation models VISSIM and CORSIM running with the virtual adaptive control software. Such simulation tools allowed creation of various traffic flow scenarios and evaluation of the actual adaptive control algorithms in the best way possible. Two signalized arterials in Las Vegas were selected to establish the simulation networks. The Boulder Highway network was used for establishing the VISSIM-SCATSIM platform and a section of Washington Avenue was used for establishing the CORISM-ACS Lite platform. The Boulder Highway network was classified as a major arterial with high traffic volumes and large intersections. The network used for the analyses included a total of 10 signalized intersections. The Washington Avenue network was classified as a minor arterial with several intersections having the side street phases being the main and coordinated phases, thus it was considered as a non-typical arterial. The Washington Avenue network involved a total of 11 signalized intersections. The weekday PM peak traffic volumes and signal timing plans were used to establish the base cases, based on which various cases and scenarios were derived for the simulation analyses. Such derived cases and scenarios included "Special Events", "Distinctive Directional Flow", "Incidents", "Detector Failure" and "New Land Developments". Each case and scenario represented a unique traffic flow pattern that was significantly different from the normal conditions.

The evaluation was based on side-by-side comparisons between the performance measures of ATCSs and optimized TOD actuated coordinated timing plans. Selected measures of effectiveness (MOE) included "Delay", "Stopped Delay", "Stops", "Travel Time", and "Queue Length". And these MOEs were obtained and compared at three levels: network, route, and node/intersection. Based on the results of the simulation analyses, conclusions were drawn and preliminary guidelines were developed for future ATCS deployments and operations.

Findings and Conclusions

SCATS

The SCATS evaluation involved a total of 27 scenarios which were classified into seven different cases under five demand levels. Major findings from the evaluation are summarized as follows:

- Based on the Network Level MOEs, SCATS consistently showed better performance at the higher traffic demand levels than TOD control. In our analyses, such higher traffic demand levels resembled demand exceeding capacity at the key intersections in the system. SCATS did not show any improvement under low and medium demand levels.
- For the Node Level performance, SCATS was good at balancing the delays and queues at the critical intersections. It was more evident at the Medium High and High demand levels. However, for the Route Level performance, SCATS did not show any advantage over TOD control. This was because SCATS treated the major street and minor street equally to obtain the overall network optimization while the TOD plans tended to favor main street movements and coordination.
- SCATS achieved better results in minimizing delays than stops. Therefore, the higher number of stops may be an indication of less optimal progression, which could be enhanced through its operating algorithm or modifying the objective functions in the SCATS setup.
- SCATS showed better performance for the "New Development" case, suggesting that SCATS can better handle significant traffic demand growth than TOD plan without a major re-timing effort. However, mixed results were observed for other special cases. For the "Special Event" case, SCATS did not show any improvement. For the "Directional Flow" cases, SCATS showed improvement only at the Medium High or High demand levels. Some "Detector Failures" did not show a significant impact on SCATS performance, but when the detectors on both major and minor streets failed, SCATS performed poorly.
- The performance of any SCATS installation, and therefore the SCATS algorithms, are significantly a function of several factors, including the characteristics of the underlying traffic control configuration within SCATS, the objectives of that configuration, and the expected operating traffic conditions. The less satisfactory results under the low and medium demand levels seemed to be contributed by the minimum cycle time setup in SCATS. This minimum cycle time was due to constraints of pedestrians crossing the very wide main street, which is not common at typical urban arterials. A lower minimum cycle time would perhaps be more suitable for the lower and medium demand levels simulated, but the experiment was not carried out due to time constraints.
- Some major limitations were noted and may have contributed to SCATS non-optimal performance under some cases. One was related to video detection issues and the other was related to the highly congested triangle area of the

network. Use of video detection at the network signals placed significant constraints to where detection zones needed to be drawn. In many cases, the number and location of the detectors could not be placed ideally. The same constraints applied to the simulation setup because of a direct adoption of the field database. The other limitation was the rigid setup by RTC/FAST engineers at the triangle area which did not give much flexibility for SCATS to adapt.

- It should also be noted that SCATS was compared with a highly optimized TOD plan under the general cases. A highly optimized TOD plan developed based on specific traffic conditions is expected to perform better than any adaptive traffic control systems. However, TOD plan will deteriorate over time, but adaptive systems such as SCATS can prolong over a longer time period as evidenced by the results under the high traffic demand levels.

ACS Lite

Following a similar study scheme, evaluation of ACS Lite resulted in the below major findings and conclusions:

- ACS Lite and the optimized actuated coordinated TOD signal timing showed very similar performance under normal traffic conditions. The results did not show which system performed better or worse, which was consistent with a stated ACS Lite design principle of "do no harm".
- ACS Lite showed better performance at higher demand levels and under sudden demand increase situations, such as the "Special Events" and "New Development" cases. This result suggested that ACS Lite can better handle traffic demand increase and flow variation than TOD plan.
- The performance potential of ACS Lite system may have not been evaluated thoroughly because the timing plan configurations were significantly restricted by the software interface in CORSIM. One particular example was that the virtual ACS Lite was limited to leading left-turn phasing only.

Guidelines for General ATCSs Applications

One of the objectives of this research was to develop recommendations and guidelines for implementing ATCSs in Nevada's urban areas. It is important to note that the guidelines provided in this document were only considered preliminary. The guidelines were developed based on the significant limitations noted in both Sections 2 and 3.

- An ATCS may be considered if more than one intersection in a signal network has a peak hour volume-to-capacity ratio above 1.2, which can cause high congestion of the entire network, or if growth in traffic demand is expected to push one or more intersections in the network to conditions where the volume-to-capacity ratio is greater than 1.2.
- ATCSs should not be considered if more than 80 percent of the intersections in a signal network have a volume-to-capacity ratio below 0.75, and no significant

growth of traffic demand is expected for the next 5-10 years.

- An ATCS may be considered if significant variations of traffic demand exist at more than one location in a signal network due to cases of special events or significant changes of land use developments near the network.
- It is also important to consider the following factors before implementing an ATCS. The operational objectives must be clearly defined when making decisions on implementing ATCSs. ATCSs tend to achieve balanced service for all vehicle movements, thus minimizing delay tends to be of higher priority than minimizing arterial stops.
- A reliable detection system should be in place for an ATCS to achieve the expected performance. Signal systems of large intersections with video detection systems may impose major limitations to camera setup and detector layout unless more cameras can be deployed to have an adequate coverage of the detection areas.
- A reliable communication system should also be in place for an ATCS. While not modeled specifically, interrupted communications will force intersections to run in a less than optimal plan and may disrupt coordination if communications are not operational for an extended length of time.
- Easiness of system setup and parameter modification seems to be a major factor affecting an agency's decision. The agency needs to understand that any adaptive system will be different from what they are used to operating and maintaining, and to be both prepared for the time that it will take to learn how to effectively manage it, as well as be prepared to contact the system provider with any questions, as not every scenario can be trained for.

Abstract

The primary goal of this research was to assess whether and how adaptive traffic control systems (ATCSs) might be applied in Las Vegas and other Nevada urbanized areas as a cost effective means of reducing traffic congestion and air pollution. The two primary objectives associated with this goal were: (1) to provide a comprehensive evaluation on selected ATCSs for their operational efficiency; and (2) to develop guidelines for best implementing ATCSs in place of traditional closed-loop or centralized signal control systems. Two ATCSs were evaluated in this study: SCATS and ACS Lite. Software-in-the-loop traffic simulation platforms were established which involved microscopic traffic simulation models VISSIM and CORSIM running with the virtual adaptive control software. Such simulation tools allowed creation of various traffic flow scenarios and evaluation of the actual adaptive control algorithms in the closest way possible. Two signalized arterials in Las Vegas were selected to establish the simulation networks. A section of Boulder Highway arterial was used for establishing the VISSIM-SCATS platform and a section of Washington Avenue was used for establishing the CORISM-ACS Lite platform. The weekday PM peak traffic volumes and signal timing plans were used to establish the base cases, based on which various cases and scenarios were developed for the simulation analyses. The evaluation was based on side-by-side comparisons between the performance measures of ATCSs and optimized time-of-day (TOD) actuated coordinated timing plans. Based on the results and some limitations noted in the report, it was found that ATCSs generally showed better performance under high traffic demand levels. Under low traffic demand levels, ATCSs did not show much benefit compared to TOD timing plans. There were mixed results under conditions of special events and other abnormal traffic events when traffic flow patterns significantly deviated from the base cases.

Keywords: adaptive traffic control system, coordination, simulation, traffic signal system, SCATS, ACS Lite.

0 Introduction

The Regional Transportation Commission of Southern Nevada (RTCSN) conducted a pilot project in early 2008 when SCATS, an adaptive traffic control system (ATCS) was implemented and evaluated along a section of Boulder Highway in Las Vegas. It was expected that the outcome of the pilot project would produce preliminary recommendations and guidance for ATCSs applications from the benefit-cost perspective, thus strategic decisions could be made on whether more adaptive systems should be deployed in Nevada's urban areas. In order to provide a comprehensive evaluation of ATCSs, various traffic and signal system conditions need to be thoroughly analyzed. This research project was initiated specifically for this purpose. The primary objectives of this project were: (1) to provide a comprehensive evaluation on selected ATCSs for their operational efficiency; and (2) to develop guidelines for best implementing ATCSs in place of traditional closed-loop or centralized signal control systems. To achieve these objectives, ATCSs need to be evaluated against actuated coordinated time-of-day (TOD) plans under a wide range of traffic flow conditions.

The project involved two major ATCSs: SCATS and ACS Lite. SCATS was developed by the Roads and Traffic Authority of New South Wales, Australia. Currently, there are more than 50 deployments worldwide and more than 10 locations in the U.S. considered to be one of the most widely used ATCSs (*1*, *2*). ACS Lite was initially developed by the FHWA in partnership with Siemens ITS, the University of Arizona and Purdue University. The system offers small and medium-sized communities a low-cost traffic control system that operates in real time, adjusts signal timing to accommodate changing traffic patterns, and eases traffic congestion (*3*, *4*). The evaluation of ATCSs in this study was primarily focused on these two systems: SCATS and ACS Lite.

This report consists of the following sections. After the introduction, a comprehensive literature review was conducted to document the state-of-the-art and the state-of-the-practice of ATCSs. The evaluation process and results of SCATS and ACS Lite were then presented, which included the development of the simulation platforms, simulation schemes and analyses results. Based on the results of the literature review and the simulation evaluation, preliminary guidelines were developed for ATCS implementations. Finally, major findings and conclusions from this study were summarized.

1 Literature Review

A comprehensive literature review is provided in this section. The review focused on the following major aspects: (1) commonly deployed ATCSs in the U.S. and other countries; (2) features and functions of different ATCSs; and (3) evaluation studies based on field tests or laboratory experiments.

1.1 An Overview of Adaptive Traffic Control Systems (ATCSs)

ATCSs are the third generation of urban signal control systems after pre-timed and traditional coordinated signal systems (*5*). Unlike closed loop or centralized signal control systems, ATCSs use real-time traffic data to optimize signal timing parameters such as cycle length, splits, and offsets, so as to minimize traffic delays and stops. One significant difference between ATCSs and traditional closed-loop or centralized systems is that ATCSs can proactively respond to real-time traffic flow changes, thus are expected to be more efficient for signal system operations.

The concept of adaptive signal control was first conceived by Miller in 1963, when he proposed a traffic signal control strategy that was based on an online traffic model. The model calculated what was called time wins and losses, and combined these criteria for different stages into a performance index (*6*). However, the first real-world application did not occur until the early 1970's when Sydney Coordinated Adaptive Traffic System (SCATS) was first implemented in Australia (*7*). A few years later, Split, Cycle and Offset Optimization Technique (SCOOT) was developed and implemented by the UK Transport Research Laboratory (*8*, *9*).

After wide applications of SCOOT and SCATS in different countries, the FHWA sponsored several ATCSs developments, including Optimized Policies for Adaptive Control (OPAC) (*10*), Real-Time Hierarchical Optimized Distributed Effective System (RHODES) (*11*) and Adaptive Control Software Lite (ACS Lite) (*12*). Nevertheless, the number of ATCS deployments in the U.S. is still limited. Currently, there are only about 30 system deployments in the U.S., and more than 95% of the coordinated traffic signals are still under the traditional closed-loop or centralized computer control system (*13*). Table 1.1-1 contains a summary of all the system deployments. Table 1.1-1 is based on the database maintained by the Research and Innovative Technology Administration (RITA) of the U.S. DOT (*13*). This database was established based on surveys conducted between 2004 and 2007 of all the major metropolitan areas. As noted in the table, although the number of signals under ATCS control is listed, no specific ATCS type is given. In some cases, very few signals (e.g., one or two) are listed under ATCS control. It is suspected that some agencies may have interpreted "adaptive" systems differently. To further confirm the accuracy of the data presented in Table 1.1-1, the research team contacted both FHWA personnel and ATCS vendors about the latest information of ATCS deployments. Figure 1.1-1 shows the geographical distribution of the ATCS deployments in the U.S. based on the latest information.

Table 1.1-1 Summary of ATCS Deployments in the U.S.

Metropolitan Area	State	Signalized Intersections		
		With ATCSs	Total Operated	Percent
Albany, Schenectady, Troy	NY	71	436	16%
Atlanta	GA	73	6099	1%
Chicago, Gary, Lake County	IL	1158	8632	13%
Dayton, Springfield	OH	4	639	1%
Denver, Boulder	CO	23	3085	1%
Detroit, Ann Arbor	MI	701	5109	14%
Grand Rapids	MI	2	760	<0.2%
Greensboro, Winston-Salem, High Point	NC	28	959	3%
Hampton Roads	VA	29	1432	2%
Houston, Galveston, Brazoria	TX	36	3877	1%
Jackson	MS	1	321	<0.4%
Little Rock, North Little Rock	AR	4	377	1%
Los Angeles, Anaheim, Riverside	CA	174	6137	3%
Milwaukee, Racine	WI	3	1508	<0.2%
Minneapolis, St. Paul	MN	6	3002	<0.2%
Modesto	CA	2	336	1%
New York, Northern New Jersey	NY	985	18349	5%
Orlando	FL	44	1527	3%
Philadelphia, Wilmington, Trenton	PA	178	4443	4%
Providence, Pawtucket, Fall River	RI	1	361	<0.2%
Raleigh-Durham	NC	7	906	1%
Richmond, Petersburg	VA	370	1088	34%
San Diego	CA	11	2885	<0.4%
San Francisco, Oakland, San Jose	CA	13	2885	<0.4%
Tampa, St. Petersburg, Clearwater	FL	76	2040	4%
Tucson	AZ	13	570	2%
Tulsa	OK	1	80	1%
Washington	DC	869	2457	35%
Total		**4883**	**80300**	**6%**

*Data Source: RITA of US DOT

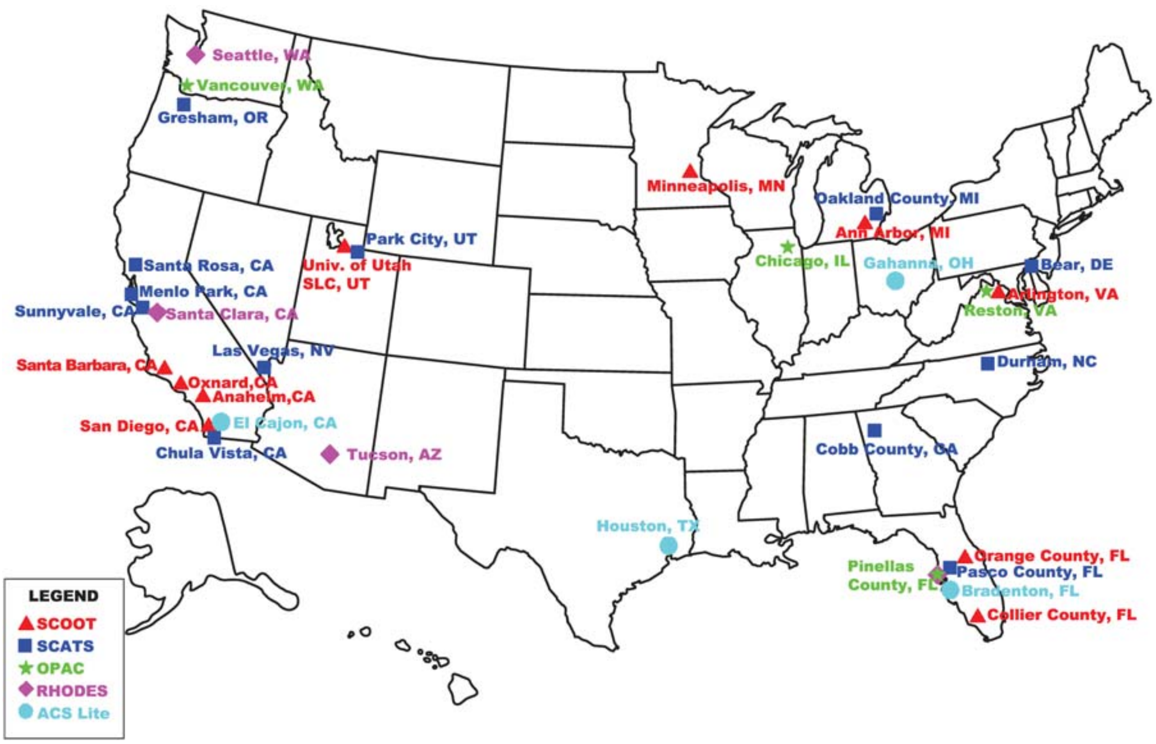


Figure 1.1-1 Geographical Distribution of ATCS Deployments in the U.S.

A national survey conducted in 2002 revealed the following main reasons for the limited number of deployments in the U.S. (*14*, *15*):

- Concerns on shortage of personnel with the required expertise; additional training requirements due to the complexity of the system; the need for management that fully supports the project; the need for a full commitment and willingness of operational and maintenance personnel to try new technologies;
- Concerns for actual system performance and benefits; uncertainties regarding system's performance for site specific conditions; preference for arterial progression rather than delay-based coordination; and
- Concerns for the deployment and maintenance costs.

Based on the limited number of deployments in the U.S., field tests and evaluation studies revealed mixed results. The majority of the studies indicated improvements over the traditional systems. For example, the City of Gresham, Oregon deployed SCATS in 2005 at a 5-lane major arterial of 11 traffic signals. A field evaluation showed that SCATS improved travel time and stops for both main street and side streets over the optimized time-of-day timing plans (*16*). However, a study on the deployment of SCATS at a 15-signal arterial in Cobb County, Georgia showed no improvement in either customer satisfaction or actual field travel time studies (*17*). One of the conclusions from this study was that adaptive traffic control systems cannot further improve system performance if the signals have already been operating under the optimized signal timing plans. It should be realized that adaptive signal-control systems are not the ultimate solutions to signal coordination. Their effectiveness heavily relies on traffic and network conditions. Nevertheless, such applicable conditions have not been fully studied, which create dilemmas for transportation agencies to determine where and when adaptive signal systems should be deployed. This proposed research specifically addresses such issues and agency needs.

1.2 Features of ATCSs

This section of the literature review contains a detailed review of the functions and features of five major ATCSs. These systems include SCOOT, SCATS, OPAC, RHODES, and ACS Lite. It is important to note that, in some literature, OPAC is also called MIST, which stands for Management Information System for Transportation. In fact, OPAC is a core part of MIST which was developed by Telvent Farradyne. Table 1.2-1 is a summary of these systems with brief descriptions of their development dates and main functions and features.

Table 1.2-1 Summary of Commercial Adaptive Traffic Control Systems

System	Year and Place Developed	Features and Methodologies	Number of Deployments
SCOOT	1970 / UK	Optimizes Splits, Cycle and Offsets; real-time optimization of signal timing	More than 200 locations worldwide; around 10 locations in the U.S.
SCATS	1970 / Australia	Optimizes Splits, Cycle and Offsets; selects from a library of stored signal timing plans	More than 50 locations worldwide; more than 10 locations in the U.S.
OPAC	1990 / USA	The network is divided into independent sub-networks	4 locations in the U.S.
RHODES	1990 / USA	Mainly for diamond interchange locations	4 locations in the U.S.
ACS Lite	1990-2006 / USA	Operates with predetermined coordinated timing plans; automatically adjust splits and offsets accordingly	4 locations in the U.S.

From the table above, it can be seen that SCOOT and SCATS are the mostly deployed ATCSs.

1.2.1 SCOOT

SCOOT is perhaps the most widely-used adaptive traffic control system with over 200 implementations throughout the world (*6*). The SCOOT system divides a network into "regions", each containing a number of "nodes" (signalized intersections and pedestrian crossings which run at the same cycle time to allow coordination). Nodes may be "double cycled" (i.e. operate at half of the system cycle length) at pedestrian crossings of under-saturated intersections. Regional boundaries are located at long links where coordination may not be feasible (*9*). The performance of SCOOT significantly relies on traffic flow data obtained from the detectors. The system requires a large number of detectors located at pre-determined locations at every link. The location of detectors is critical, typically placed at the upstream end of the approach link.

SCOOT has three optimization procedures: the Split Optimizer, the Offset Optimizer, and the Cycle Time Optimizer (9). The algorithm predicts vehicle delays and stops at each link, and calculates the system's *performance index* based on these measures. From the overall performance of the network, SCOOT incrementally changes the pre-determined signal timing plans. Before making changes to the phase splits, the Split Optimizer evaluates the current red and green splits to determine whether the splits should be extended, shortened or remain the same. The Split Optimizer works in increments of one to four seconds.

The Offset Optimizer adjusts the offset values every cycle for each intersection. The system uses the cyclic flow data to analyze the current travel time and to predict the offset for each link between upstream and downstream intersections. It then evaluates whether the existing offset should be extended, shortened or remain the same in four-second increments.

The Cycle Time Optimizer finds the most saturated intersection named the "critical node". The system will attempt to adjust the cycle length to maintain this intersection with 90% saturation for each phase/movement. If the algorithm requires cycle time to be changed, the optimizer can increase or decrease the cycle length in 4, 8 or 16 second increments (9). Each intersection can run a double cycle with a restriction of saturation of no more than 90%. Conversely, when the degree of saturation rises above 90%, the intersection returns to a single cycle (18).

With the above described optimizers, SCOOT can actually change signal timing plans according to traffic flow fluctuations in different time periods. It can also follow daily traffic flow trends over time and maintain a constant coordination of the signal network (9).

1.2.2 SCATS

SCATS is probably the most advanced and widely used adaptive traffic control system. SCATS was developed by the Roads and Traffic Authority of New South Wales, Australia (1, 2). As a real-time adaptive signal control system, SCATS can adjust signal timing in response to fluctuations in traffic flow and system capacity.

SCATS is designed with three control levels: central, regional and local. For each intersection, SCATS distributes computations between a regional computer at the traffic operations center and the field controller. The central level is operated by the central computer, which communicates with other levels in the hierarchy, primarily for monitoring purposes.

At the regional level, a number of signals are grouped into a subsystem up to ten intersections, which is controlled by a regional computer to coordinate signal timings. The SCATS uses traffic volume data to calculate *Degree of Saturation* and *Car Equivalent Flow* for each approach lane. These parameters are critical for selecting control strategies, for example, Degree of Saturation is used to determine cycle length and split, and Car Equivalent Flow is used to determine offset plans.

The optimization algorithm typically adjusts cycle length up to six seconds per cycle; however, it can be increased to nine seconds under the circumstance of detected significant variation. Phase splits can vary up to 4% of the cycle length in each cycle. The reason for the 4% change limit is to prevent excessive negative impact on the Degree of Saturation. The offsets of two intersections are determined in each subsystem.

At the local level, optimization occurs at the intersection within the constraints imposed by the regional computer's strategic control. Based on real-time traffic volume data from the detectors, a local controller allows early termination of phases when the demand of a movement is less than the average, and a phase can be omitted when there is no demand. All the extra green time is either added to the main street phase or can be allocated to subsequent phases.

All intersections in a subsystem operating at the same cycle length are coordinated via offsets. These subsystems can "marry" to achieve coordination using a separate set of offsets. "Marriage" and "Divorce" are controlled through a voting mechanism based on cycle length and volume.

SCATS combines adaptive traffic signal control with conventional control strategies to provide users with a system that can meet various operational needs. Control strategies include: adaptive operation, time of day and day of week coordination, and isolated signal operation. With real-time reporting tools, the system allows traffic engineers to monitor system operations. Continuous intersection monitoring quickly alerts operators of any unusual conditions or equipment failures.

1.2.3 OPAC

OPAC is a distributed control strategy featured by a dynamic optimization algorithm that calculates signal timings to minimize total intersection delays and stops. OPAC was developed at the University of Massachusetts at Lowell under the sponsorship of the U.S. Department of Transportation in the early 80s (*10*, *19*).

OPAC distinguishes itself from traditional cycle-split signal control strategies by dropping the concept of cycle (*10*). In OPAC, the signal control algorithm consists of a sequence of switching decisions made at fixed time intervals. A decision is made at each decision point on whether to extend or terminate a current phase. Dynamic programming techniques are used to calculate optimal solutions.

OPAC utilizes on-line data obtained from upstream detectors as well as historical data in its optimization process. The objective is to minimize total vehicle delays and stops. Each phase is constrained only by the minimum and maximum phase lengths. Consequently, the duration of a phase is never pre-specified. It depends solely on the prevailing traffic flow conditions. The dynamic optimization process is carried out continuously to ensure that the signal operations are always up-to-date (*10*).

OPAC experienced four major generations of development. The first generation of OPAC is OPAC-1. This type of OPAC is just a computer program to minimize total vehicle delays for individual intersections.

OPAC-2 is the second generation of OPAC families, and it is a simplified edition of OPAC-1. OPAC-2 arranges each approach's initial queue length information and the arrival rates in each interval into the optimizing algorithm, and then the system finds the optimal switching sequence which minimizes total vehicular delays (*10*).

The third generation of OPAC is OPAC-RT. This generation of OPAC is designed for real-time traffic signal control and operations. There are two versions of OPAC-RT, the second version of OPAC-RT is designed for isolated intersections. The system can handle duel-ring, eight phase controllers. But only the through phases are actually controlled by OPAC.

The latest version of OPAC is RT-TRACS, which is the network version of OPAC. This generation of the OPAC system has the following features (*20*):

- Full intersection simulation with platoon identification and modeling algorithm.
- Split optimization for up to eight phases in a dual-ring configuration.
- Configurable performance functions of total intersection delay or stops, or both.
- Optional cycle length and offset optimization.
- Free and explicit coordinated modes.
- Phase skipping in the absence of demand.
- Automatic response to changes in phase sequence.

1.2.4 RHODES

RHODES, which was developed by the University of Arizona in 1990 (*11*), is a real-time traffic adaptive control system with a hierarchical structure. RHODES can take input from different types of detectors and, based on what future traffic conditions are predicted, generate optimized signal control plans.

Three major system features were noted by the development team that makes RHODES a viable and effective adaptive signal control system (*11*). First, recent new technologies and methods are well adopted in RHODES to make sure the system has high performance in transferring, processing, predicting traffic data and signal control. Second, RHODES takes into consideration the stochastic nature of traffic flow variations. Third, explicit prediction of individual vehicle arrivals, platoon arrivals and traffic flow rates are fully considered in RHODES.

RHODES adopts three major prediction and optimization algorithms. PREDICT is an algorithm to predict future arrivals at intersections for individual vehicles. The algorithm uses the output of the detectors on the approach of each upstream intersection, together with information on the traffic state and planned phase timings for the upstream signal, to predict future arrivals at the intersection under RHODES control. APRES-NET is another prediction algorithm similar to PREDICT, however, APRES-NET predicts platoon arrivals instead of individual vehicles. REALBAND is the optimization algorithm, which aims at maximizing progression bands based on actual platoons in a network (*11*, *21*). In general, any delay or stop based measure of performance may be optimized.

1.2.5 ACS Lite

In the mid-1990s, a collection of prototype adaptive control systems (ACS) was developed by the Federal Highway Administration (FHWA). ACS Lite, a reduced-scale version of the ACS, was developed by FHWA in partnership with Siemens ITS, the

University of Arizona and Purdue University (3, 4). The system offers small and medium-sized communities a low-cost traffic control system that operates in real time, adjusts signal timing to accommodate changing traffic patterns, and eases traffic congestion. ACS Lite can be used with new signals or to retrofit existing traffic signals (22). It is designed for providing cycle-by-cycle control to closed-loop systems, which represents 90% of the traffic signal systems in the United States.

The ACS Lite software continuously monitors traffic signals and the flow of traffic, and adjusts the signal timing accordingly. These adjustments can be made on a user-specified time frame. ACS Lite is used in closed-loop systems, with no need for a central computer system since the software resides on a field-hardened processor that is located at a local traffic signal controller cabinet. The software can be deployed using as few as two traffic detectors on a roadway. Once deployed, the system is ready to operate and does not require periodic calibration (4).

The effectiveness of two offset settings at upstream and downstream intersections is measured or quantified by calculating the progressed flow or captured flow. This performance measure is a surrogate for vehicle stops and delay, which cannot be directly measured in the field from point detectors. Specifically, the captured or progressed vehicular flow is the amount of flow (in units of vehicle-seconds of occupancy) arriving at the stop line at a given point in the cycle multiplied by the percent of time the progression phase is green at that time during the cycle. The algorithm evaluates different offsets by calculating the captured flow on each approach and selecting the offset that maximizes the total amount of captured flow (23).

The ACS Lite has been field demonstrated in Gahanna, Ohio; Houston, Texas; and Bradenton, Florida. The latest field test is planned for El Cajon, California. All of the test sites showed improvement in traffic flow (21). The widely accepted benefits of using ACS Lite are as follows:

- Low cost.
- Compatible with closed loop systems.
- Operates in real time.
- Easily configured and calibrated, does not require periodical calibration.
- Proven the ability to ease traffic congestion.

1.2.6 Comparison of System Features

Based on the above descriptions of the major ATCSs, comparisons were made among system functions and features, as shown in Table 1.2-2 and Table 1.2-3.

Table 1.2-2 System Characteristics Comparison of Various ATCSs

ATCSs	Advantages	Disadvantages
SCOOT	• No need to prepare or update fixed time plans; • No sudden changes in settings – new plans continuously evolve; • Trends in behavior and growth could be followed; • System self adjusted to respond to incidents.	• Requires skilled design and validation of network models; • Affected by subsequent changes to network, land use, parking and loading; • Model information needs to be periodically reviewed.
SCATS	• The system can automatically generate timing plans; • The system can calibrate detectors automatically. This function simplifies system test and grooming.	• The location of detectors is always near the stop bar, so SCATS cannot forecast platoon and dynamically evaluate offset performance; • The performance relies on a set of pre-defined timing plans.
OPAC	• OPAC proved to be highly effective during under-saturated conditions when intersections were operating with fully actuated mode.	• Field implementations are still limited, so the system performance is based on limited cases.
RHODES	• Amenable to lab testing; • Consistent with traffic response objectives; • More efficient in utilizing the capacity of the network.	• Under-saturated conditions only.
ACS Lite	• Low Cost • Compatible with existing closed loop systems • Provides real-time signal timing solutions • Easily configured and calibrated	• Current version cannot provide cycle optimization.

Table 1.2-3 Main Features of Various ATCSs

ATCSs	Goal	Detector Layout	Hierarchical Organization	Arrival Prediction	Queue Estimation	Split Optimization	Offset Optimization	Cycle Optimization	Phase Sequence Optimization	On Saturated Condition
SCOOT	Minimize Performance Index	Upstream[1]	Central	√	√	√[2]	√	√[3]	N.A.	Poor
SCATS	Minimize Delay and Stops or Maximize Throughput	Stop bar	Central Regional Local	×	×	√	√	√	×	Good
OPAC	Minimize Stops and Delays	Both[4]	Synchronization Coordination Local	√	√	√	Optional	Optional	×	N.A.
RHODES	Minimize Cumulative Delay	Both[5]	Network Loading Network Control Intersection	√	√	√	√	√	N.A.	Poor
ACS Lite	Maximize Total Amount of Captured Flow	Both	Regional Local	√	×	√	√	×	×	N.A.

[1] Detectors deployed at least 300 ft upstream from stop bar.
[2] One third of total split is affected by optimization.
[3] Constraint by sub-area, not affected by congestion.
[4] Upstream detectors deployed at 400-600 ft from stop bar.
[5] Upstream detectors suggested at 325 ft from stop bar.

1.3 ATCSs Implementation and Evaluation Results

1.3.1 SCOOT

Field implementation and evaluation studies were primarily conducted in the UK and a few other countries overseas. In North America, less than ten places deployed the SCOOT system, and the evaluation studies mainly focused on these two cities: Toronto, Canada; and Anaheim, California. Previous studies indicated that SCOOT achieved an average of 12% reduction in delay compared with TRANSYT fixed-time plans (*24*). SCOOT may obtain an extra 3% reduction in delay every year when fixed-time plans are used due to traffic volume increases (*25*).

Actual field implementations and evaluations started in 1981 when SCOOT first began operations in two areas in Coventry, UK. The field results showed that SCOOT was able to reduce 4%-8% of travel time and 22%-33% of delays. Later, SCOOT was deployed and tested in London around the area of Westminster. It achieved 6%-8% reduction in travel time, and 19% reduction in delay and 5% reduction in stops (*26*). The system deployed in Southampton between 1984 and 1985 showed 18%-26% reduction in travel time and 1%-48% reduction in delays (*27*). Similar results were observed for the system deployed in the City of Worcester (*28*). In the late 1990s, when bus priority was equipped with SCOOT in London, the average bus delays were reduced by 7%-13% (*29*).

SCOOT's worldwide deployment started during the early 1990s, in China (*30*), São Paulo, Brazil (*31*); and Nijmegen, Netherlands (*32*). Table 1.3-1 provides a summary of the worldwide evaluation results, except for the studies in North America.

Table 1.3-1 SCOOT Implementation Results Worldwide

Place	Previous Control System	Travel Time	Delay	Stops
Coventry, UK	Fixed-time TRANSYT	-8 to -4%	-33 to -22%	N.A.
London, UK	Fixed-time	-8 to -6%	-19%	-5%
Southampton, UK	Isolated Actuated	-26 to -18%	-48 to -1%	N.A.
Worcester, UK	Fixed-time TRANSYT	-11 to -3%	-20 to -7%	N.A.
Beijing, China	Fixed-time Uncoordinated	-16 to -2%	-41 to -15%	-33 to -14%
São Paulo, Brazil	Fixed-time TRANSYT	N.A.	-20%	N.A.
Nijmegen, the Netherlands	Fixed-time	-25 to -11%	-33 to -25%	N.A.

* Data Source: References *26* - *32* and http://www.scoot-utc.com/GeneralResults.php.
Note: "-" means reduction.

Toronto, Canada deployed the first SCOOT system in North America in 1995 (*33*). An earlier pilot evaluation study found that SCOOT was able to reduce travel time by 8%, shorten delays by 17%, and decrease stops by 22%. Meanwhile, SCOOT could save 5.7% of total fuel consumption, decrease hydrocarbons by 3.7%, and reduce monoxide emissions by 5.0%. Four years later, a more comprehensive evaluation was conducted by Greenough (*34*), and the results from the study are shown in Table 1.3-2 with various performance measures.

The implementation of SCOOT in Anaheim, California seemed to have encountered some "unusual" situations (*35*, *36*). The study in Anaheim used a before-and-after approach, with ten observations before the implementation and ten after. Travel times were determined using the floating-car technique on five routes before and after the implementation. Unlike other results, there were mixed results regarding travel time improvements. For example, the travel times for the routes ranged from a decrease of 10% to an increase of 15%. SCOOT's performance relative to the baseline system was better under event conditions than under nonevent conditions.

Overall, the SCOOT system performance was very good in most cities and countries based on field implementation results as shown above.

Table 1.3-2 SCOOT Implementation Results in Toronto

Items	Performance Measures
Traffic Flow Speeds	+3 to +16%
Left Turn Violations	-71%
Rear-end Conflicts	-24%
Ramp Queues	-14%
Intersection Stops	-29 to -18%
Intersection Delays	-42 to -10%
Left Turn Delays	-35 to 0%
Vehicle Delays	-26 to -6%
Vehicle Stops	-31 to -10%
Vehicle Travel Time	-11 to -6%
Pollution Emissions	-6 to -3%
Fuel Consumption	-7 to -4%

* Data Source: Reference (*34*).
Note: "-" means reduction; "+" means increase.

1.3.2 SCATS

The first field implementation of SCATS occurred in the early 1970s on Princes Highway, Newtown, a 2.6 km arterial on the south side of Sydney, Australia (*1*). Compared with optimized fixed-time, initial field study results revealed travel time reductions of 39.5%, 14.5%, and 32.8%, during the morning peak, normal business hours, and the evening peak period, respectively. Other improvements achieved by this study included 20%-48% reduction in stops, 20% reduction in accidents, 7% reduction in fuel consumption, and 13%-25% reduction in CO emissions.

The first major SCATS implementation and study in North America occurred in the early 1990s in Oakland County, Michigan. The SCATS adaptive signal control system in Oakland was a part of the Road Commission's FAST-TRAC project. At its completion, FAST-TRAC involved the conversion of more than 1,000 pre-timed and actuated signalized intersections to SCATS control and established a county-wide, real-time route navigation system (*37*). In 1994, the first evaluation study showed that the SCATS system reduced the number of stops by 33%. Seventy-two percent of the surveyed drivers indicated improved driving experiences after SCATS was implemented (*38*). In addition, crash frequency declined in Oakland County due to the new FAST-TRAC system (*39*).

In 1998, another study was conducted to compare the travel times before and after implementation of SCATS on a 3.1-mile arterial corridor in Oakland County. The results indicated that travel time decreased by 8.6% in the morning peak direction of travel and 7% in the evening peak direction of travel. Off peak and noon-peak direction travel times were also reduced by 6.6% - 31.8%. The improved travel times observed on this major arterial, however, lead to increased average delay on minor street approaches (*40*). A third evaluation study on the Oakland County's SCATS system was completed in 1999. The third study aimed at examining the relationship of major and minor street delays under the SCATS control and fixed-time signal control. It was found that SCATS tended to allocate more green time to left turn traffic compared with the fixed-time system (*37*).

Several SCATS implementation and evaluation studies were conducted in the past 14 years in some U.S. urban areas. In 2007, a field test of SCATS was conducted in Gresham, Oregon (*41*). The site was a 1.88 mile long north-south arterial with 11 signals. Compared to two-year old coordinated signal timing plans, 5%, 6% and 12% reduction of travel time, vehicle delay and number of stops were obtained on weekdays; and there were 8%, 16% and 18% reduction on weekends.

In early 2008, the University of Utah finished a SCATS evaluation study, in which SCATS showed improved travel times, delays and number of stops in Park City, Utah (*42*). The travel times and delays on the major route in the Park City network were always shorter with SCATS control than with TOD plans. The improvement was more significant during the AM peak period.

While most published reports indicated operational improvements with SCATS, one particular study conducted in Cobb County, Georgia showed no significant change compared with optimized TOD plans (*43*). It was concluded that SCATS may not increase drivers' daily satisfaction with their roadway experience if the corridor is already optimally timed; however, drivers did notice the improvements during non-recurring incident conditions. The report also mentioned that adaptive systems might have long term cost benefits due to possibly lower maintenance expenses than traditional coordination systems. Table 1.3-3 provides a summary of the SCATS evaluation results in the U.S.

Table 1.3-3 Summary of SCATS Implementation Results in the U.S.

Place	Previous Control System	Detail	Travel Time	Delay	Stops
Oakland County, MI	Optimized Fixed-Time		N.A.	-6 to +33%	-33%
Gresham, OR	Coordinated	Weekday	-5%	-6%	-12%
		Weekend	-8%	-16%	-18%
Park City, UT	Coordinated	AM Peak	-8%	-19%	-18%
		PM Peak	-4%	-12%	+1%
		Weekend	-2%	-13%	-5%

* Data Source: Reference (*38*, *41*, *42*).
Note: "-" means reduction; "+" means increase.

1.3.3 OPAC

The first field implementation and test of OPAC occurred in Reston Parkway in Northern Virginia at the end of 1997 (*44*). Reston Parkway is a four-lane arterial with 16 signals.

The project provided valuable insights into the performance of OPAC under various traffic conditions and site geometry. Field results showed 5% - 6% reductions in average delays and stops compared with a well-tuned fixed-time system that was in place (*19*).

In the same year, another field test of OPAC was conducted at a site in New Brunswick, New Jersey (*45*). The site was a 17 km-long north-south arterial with 15 signals. In this study, comparisons of traffic performance were made between two conditions: one with the conventional signal control and one with the OPAC control. The study showed OPAC's best performance was during oversaturated conditions in the southbound direction with 26% reduction in travel time and 55% reduction in stops. However, some side-street approaches experienced larger delays and more stops. OPAC also proved to be highly effective during under-saturated conditions when intersections were operating in a fully actuated mode.

The latest OPAC implementation was at a site in Pinellas County, FL in 2007 (46). The evaluation area on US19 was located between Curlew Road and Tarpon Avenue, a 6.75-mile stretch that includes eight signalized intersections within the 11.5-mile deployment route. The before/after test results of the data showed that the travel times through the section of US19 with OPAC were reduced between 2%-25% with an average reduction of 7.5%. After implementation of the new software, the travel time dropped from an average of 19 minutes to 14.5 minutes. The most dramatic benefits were shown in the peak period travel times. In the AM and PM peak periods, the software reduced travel times in the primary direction by an average of 25%. Unfortunately, the type of signal control system before OPAC installation was not given in the report. Extracted from three sources, covering both self-evaluations and independent research, a selection of OPAC implementation results are summarized in Table 1.3-4.

Table 1.3-4 Summary of OPAC Implementation Results in the U.S.

Place	Previous Control System	Travel Time	Delay	Stops
Reston, VA	Optimized Fixed-Time	N.A.	-6 to -5%	-6 to -5%
New Brunswick, NJ	Coordinated	-26 to -4%	N.A.	-66 to +39%
Pinellas County, FL	Coordinated	-25 to -2%	N.A.	N.A.

* Data Source: Reference (*19*, *45*, *46*).
Note: "-" means reduction; "+" means increase.

1.3.4 RHODES

In a study conducted by Mirchandani and Head (*11*), the authors mentioned, after a simulation testing of RHODES, three field tests were planned, one for a ten-intersection arterial segment in Tucson, AZ, a nine-intersection arterial segment in Seattle, WA, and a diamond interchange in Tempe, AZ. However, only one published document was found for the deployment site in Seattle. In the report, the evaluation was only done on a qualitative basis. A general conclusion was that no significant change in delay or travel time was found with the RHODES system (*14*). Also, no specific information was given for the signal system before RHODES.

Apparently, there was a recent RHODES implementation that occurred in 2007 in Pinellas County, Florida after the above studies (*46*). The system was deployed at a 5.5-mile long section of State Route 60 that included 17 signalized intersections between

Damascus Avenue and Hillcrest Avenue. The preliminary results showed that travel times were reduced by1%-15% with an average reduction of 8%. Similarly, no signal control information before RHODES was provided. All other reported RHODES results were based on simulation studies. In Tucson, Arizona, analytical models indicated that adaptive signal control in conjunction with transit signal priority can decrease delay on main streets by 18.5%, and by 28.4% for the side streets (47). The field evaluation results of RHODES are summarized in Table 1.3-5.

Table 1.3-5 Summary of RHODES Implementation Results in the U.S.

Place	Previous Control System	Detail	Travel Time
Seattle, WA	N.A.	AM Peak, Route 1	Indeterminate
		AM Peak, Route 2	Indeterminate
		AM Peak, Route 4	Better
		AM Peak, Route 5	Better
		PM Peak, Route 1	Indeterminate
		PM Peak, Route 2	Worse
		PM Peak, Route 4	Indeterminate
		PM Peak, Route 5	Worse
Pinellas, FL	N.A.	-	-15 to -1%
Tucson, AZ	Simulation	Main Street	-18.5%
		Side Street	-28.4%

* Data Source: Reference (14, 45, 47).
Note: "Indeterminate" means no marked improvement after RHODES deployed; "Better" means RHODES has better result; "Worse" means RHODES has worse result; "-" means reduction.

1.3.5 ACS Lite

ACS Lite was integrated with traffic controllers from four manufacturers, namely Siemens ITS, Econolite Inc., McCain Inc., and Peek Inc. The system was field tested at four locations across the U.S. These four locations include a 1.4-mile Hamilton Road section with nine signals in the City of Gahanna, OH (48), a 2.1-mile section of State Route 6 with eight signals in the City of Houston, TX (49), a 2.9- mile section of State Route 70 with eight signals in the City of Bradenton, FL (50), and a 1.9-mile section of Main Street with ten signals in the City of El Cajon, CA (51). The evaluation results are shown in Table 1.3-6.

Table 1.3-6 ACS Lite Field Test Locations and Evaluation Results

Location	Vendor	Controller Model	Intersection Count	Travel Time	Delay Time	Vehicle Stops	Fuel Usage	1-Year Benefits
Gahanna, OH	Econolite	ASC/2S	9	-1%	0%	-17%	-4%	$88,000
Houston, TX	Eagle	M50	8	-11%	-35%	-29%	-7%	$578,000
Bradenton, FL	Peek	3000E	8	-12%	-28%	-28%	-4%	$757,000
El Cajon, CA	McCain	170E	10	-5%	-9%	-10%	0.8%	$327,700

* Data Source: References (48 - 51).
Note: "-" means reduction; "+" means increase.

1.3.6 Benefit and Cost Comparison

Table 1.3-7 is a benefit and cost comparison of the five ATCSs reviewed in this report.

Table 1.3-7 Benefit and Cost Comparison

ATCSs	Benefit (Percent Change in)			Initial Capital Cost (Per Intersection)
	Travel Time	Delays	Stops	
SCOOT	-29% to -5%	-28% to -2%	-32% to -17%	$30,000 to $60,000
SCATS	-20% to 0%	-19% to +3%	-24% to +5%	$20,000 to $30,000
OPAC	-26% to +10%	-	-55% to 0%	$20,000 to $50,000
RHODES	-7% to +4%	-19% to -2%	-	$30,000 to $50,000
ACS Lite	-12% to +7%	-38% to +2%	-35% to -28%	$6,000 to $10,000

* Data Source: Lecture Slide (*52*).
Note: "-" means reduction; "+" means increase.

The above table shows that ACS Lite has the minimal cost among all the systems and it requires less maintenance; however, there are some major limitations of the current software version. One limitation is that it does not provide cycle optimization, but only selects from a set of pre-defined time-of-day plans. Another limitation is that it requires upstream detectors on coordinated approaches for offset optimization. Other systems are much more expensive and need skilled staff to operate and maintain the systems. SCOOT, OPAC, and RHODES rely heavily on presence of upstream detectors for making signal timing adjustments; however, SCATS only uses stop-bar detectors.

1.4 Summary and Findings

Major findings from this literature review are summarized below:

- Compared to other countries, the number of adaptive system deployments in the U.S. is relatively small, with only about 4% of the total signalized intersections under adaptive control.
- There are various factors that have affected the low number of adaptive system deployments. These factors include: (1) concerns for the shortage of personnel with the required expertise; (2) concerns for actual system performance and benefits; (3) concerns for the initial and maintenance costs.
- According to the published literature, the majority of system deployments resulted in significantly improved traffic operations compared to traditional time-of-day coordination plans. The improvements are based on reduced stops, delays, and fuel consumption. Only one published document was found to report an unsuccessful adaptive system implementation.
- Regarding the number of system deployments, SCOOT has the largest world-wide deployments, while SCATS has the largest U.S. deployments. The number of deployments of OPAC and RHODES is limited to very few locations. Although ACS Lite also has a small number of deployments due to its short history, the number of deployments is expected to grow due to its low cost and compatibility with existing closed-loop systems.

- Regarding deployment costs, ACS Lite is the lowest, while SCOOT is the highest. The actual costs will vary significantly depending on the level of detection needed. The high cost for SCOOT is probably due to the large number of detectors required.

2 SCATS Evaluation

Evaluation of SCATS system was documented in this section. The network used for the evaluation was the Boulder Highway arterial where SCATS was implemented in the field. The traffic demand levels used in the simulation were derived based on the weekday PM peak hour traffic conditions. This traffic demand level represented a near-capacity (a v/c ratio close to 1.0) situation at the critical intersections along the arterial. For each scenario, there was a side-by-side comparison between optimized time of day (TOD) coordination plan and SCATS system using the same traffic and simulation parameters, thereby minimizing the biases caused by factors beyond the signal controls.

2.1 Development of a Simulation Platform

2.1.1 The Simulation Technique and the Platform

There are currently two types of techniques to run traffic simulation models with an actual signal control algorithm: hardware-in-the-loop simulation and software-in-the-loop simulation.

Figure 2.1-1 shows a system configuration for the hardware-in-the-loop simulation technique. In a hardware-in-the-loop environment, actual traffic signal controllers are used and a hard-wire connection is established between the simulation model and the signal controller via a device called the Controller Interface Device. While this technique provides true representation of the signal control algorithm, the main drawback is that the simulation can only be conducted in real-time, which could be time-consuming. In the area of adaptive traffic control systems, hardware-in-the-loop simulation has already become a widely adopted technique.

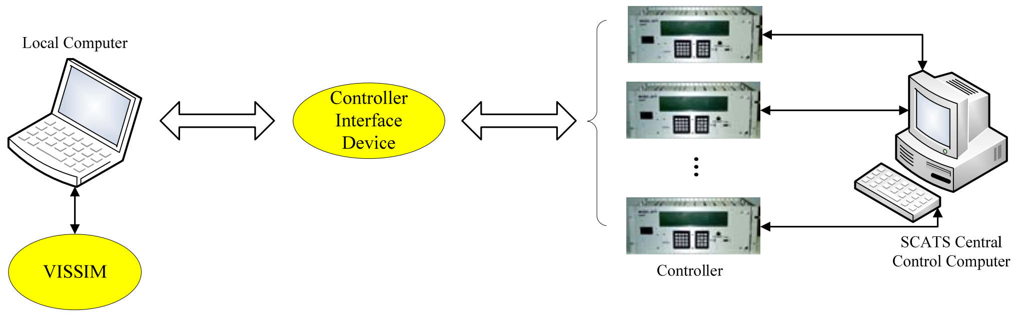


Figure 2.1-1 Hardware-in-the-loop Simulation Environment

An emerging technique to replace hardware-in-the-loop simulation is the so-called software-in-the-loop simulation (shown in Figure 2.1-2), where the signal control hardware is substituted by a software algorithm. In the software-in-the-loop simulation environment, the simulation model runs with a virtual signal control algorithm but does not require real-time simulation, thereby increasing the simulation speed significantly. The software-in-the-loop technique was adopted for this research. The virtual SCATS algorithm is called SCATSIM, and was developed and distributed by RTA, Inc. in Australia, the same vendor of SCATS. SCATSIM is compatible with interface of the VISSIM simulation model.

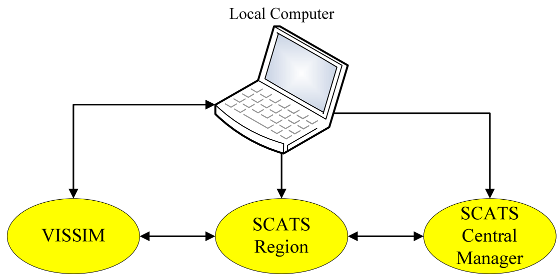


Figure 2.1-2 Software-in-the-loop Simulation Environment

SCATSIM, which includes the SCATS Central Manager and SCATS Region, has been successfully installed in a laptop computer used for this research study. Figure 2.1-3 shows a screenshot displaying a part of the VISSIM network and the SCATS operation.

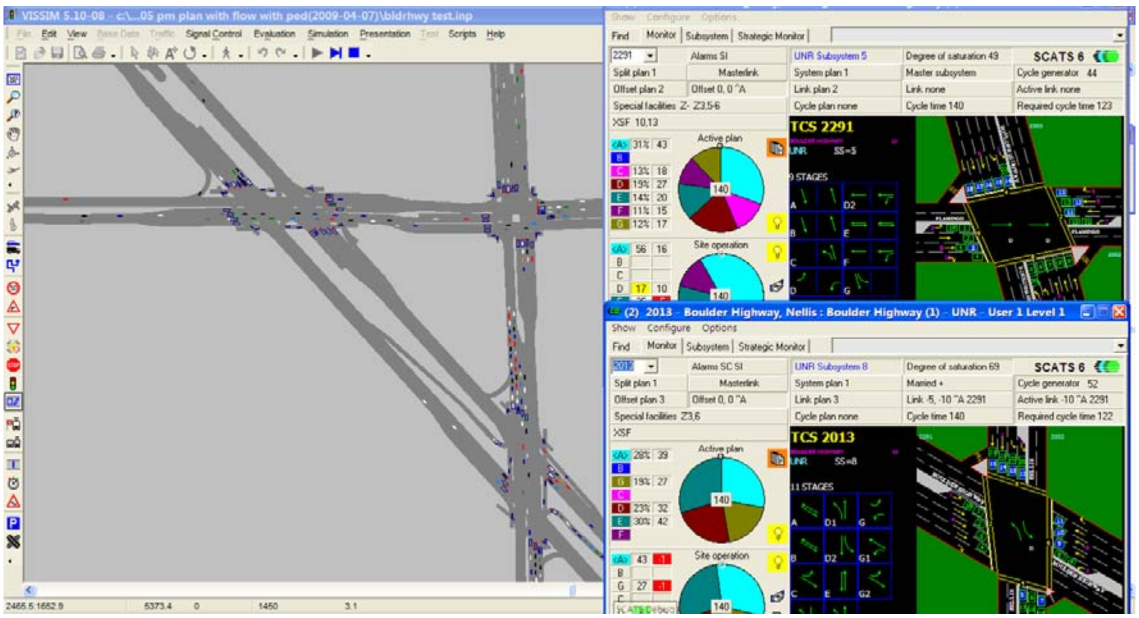
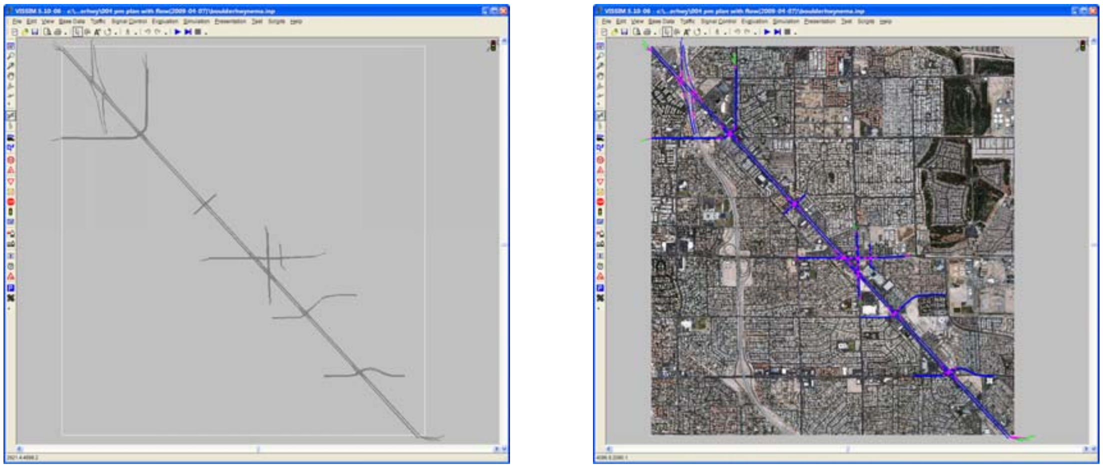


Figure 2.1-3 VISSIM and SCATS Interface

2.1.2 Model Establishment and Calibration

The segment of Boulder Highway where SCATS was implemented in the field was coded in VISSIM (see Figure 2.1-4 for a screen shot). The model was calibrated to ensure proper representation of the actual traffic flow and system characteristics.



(a) Without the Background Map (b) With the Background Map

Figure 2.1-4 The VISSIM Model for Boulder Highway

The measures of effectiveness (MOEs) used for the model calibration consisted of the travel times on a number of selected major routes. These travel times were obtained in the field in an earlier referred pilot project (53) through extensive travel time runs using the floating car technique. The calibration was based on the TOD coordination. In order to produce the best match between VISSIM results and the field data, the following major calibration tasks were involved.

- Traffic Volumes:

  Only the p.m. peak hour volumes were coded in VISSIM and the calibration was also based on the p.m. peak hour. The p.m. peak hour traffic volumes were obtained from the Boulder Highway Adaptive System Pilot Project (53). This was considered sufficient because later evaluation of SCATS involved a wide range of volume scenarios and the comparisons were based on the same calibrated VISSIM model.

- Speed Distribution:

  Speed is directly related to travel time, and is one of the major elements in VISSIM. The distribution of speed must be defined in VISSIM. While Normal distributions have been widely used to represent traffic speeds, our field observations of driver behavior at Boulder Highway revealed that vehicles generally followed each other closely. Thus, well-structured platoons were maintained even when traveling long distances along the arterial. To reflect such field observed drivers' characteristics, the traffic speed was coded as a Normal distribution with speed ranged between 42.5 mph and 50 mph, as shown in Figure 2.1-5.

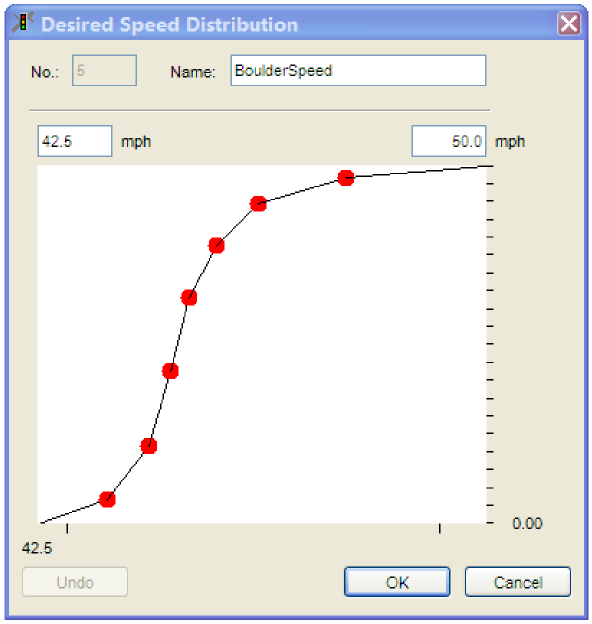
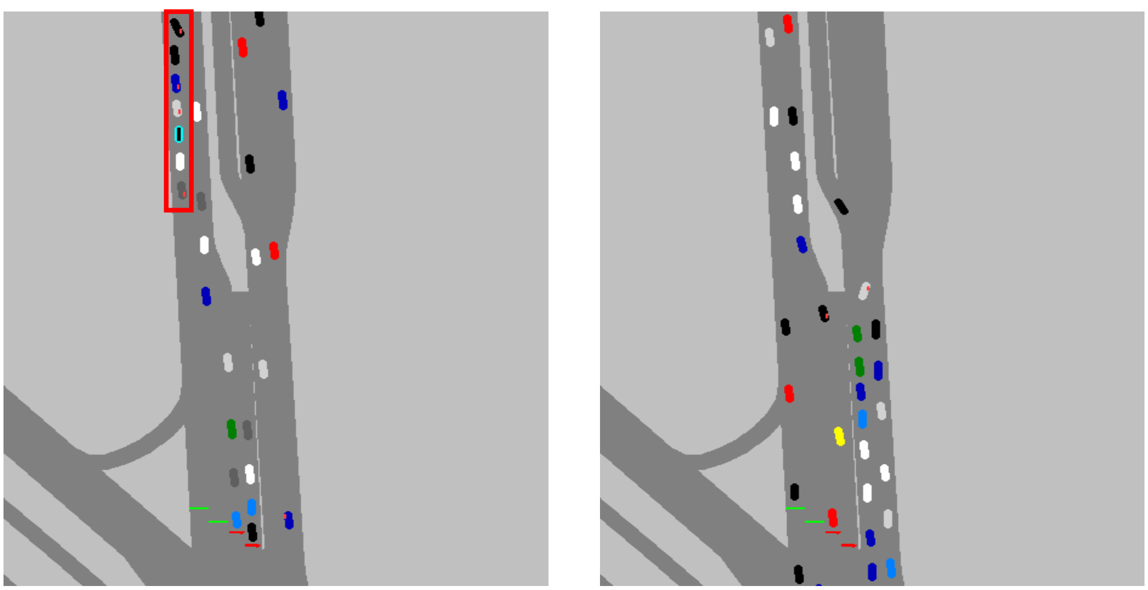


Figure 2.1-5 Speed Distribution

- Lane Changing:

  Lane changing is another major element in traffic simulation models. The default settings of VISSIM could not yield satisfactory lane changing behaviors as shown in Figure 2.1-6(a) where the left turn vehicles (circled by red rectangle) could not get to the correct lane in time, leading to unrealistic blockage to the through lane. This problem was resolved by selecting adequate parameters for "Emergency Stop" and "Lane Change" distances (see Figure 2.1-6(b) for the case after the calibration).



(a) before (b) after

Figure 2.1-6 Lane Changing Behavior

- Signal Timing:

The p.m. peak signal-timing plan was coded in VISSIM for the model calibration. It was realized that the offset in VISSIM was always referenced to the start of green of the coordinated phase in the first ring. Therefore, the offsets from the time-of-day plan were converted according to VISSIM's specifications. Other signal-timing parameters involved in the calibration included "Permissive Start", "Permissive End" and "Force off".

Figure 2.1-7 illustrates how signal timing parameters were coded in VISSIM.

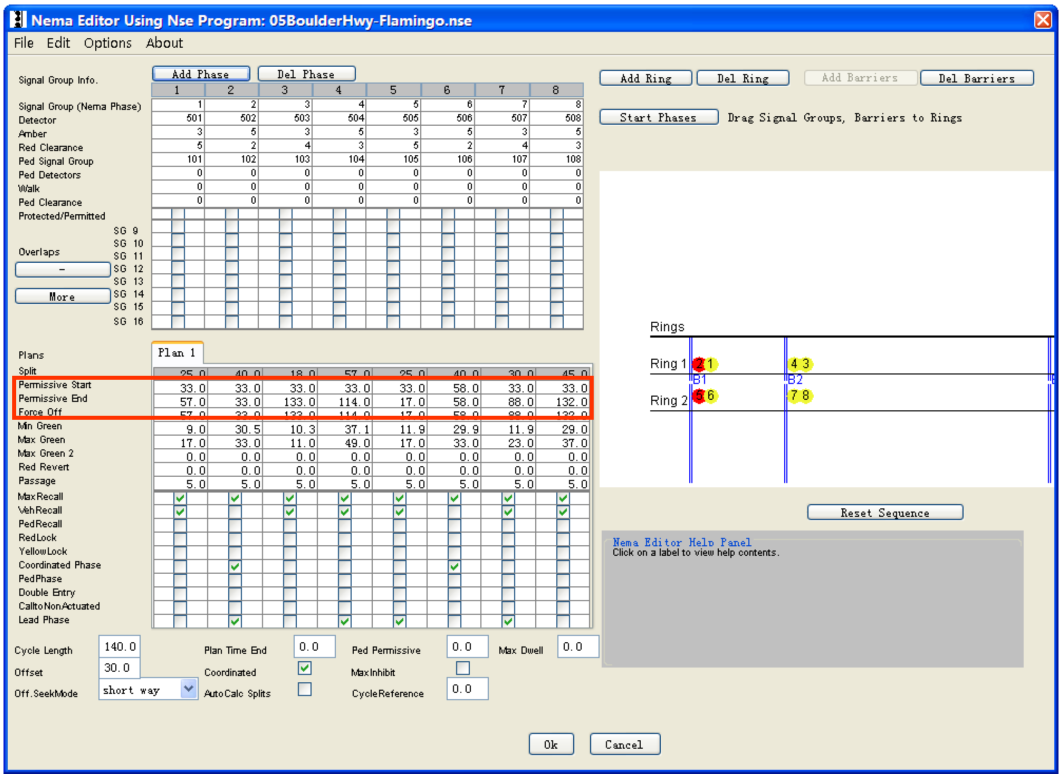


Figure 2.1-7 Signal Timing Parameters in VISSIM

- Route Travel Times

The model calibration was finally assessed based on the travel times at 17 selected routes as shown in Figure 2.1-8. These travel times were compared between VISSIM outputs and those collected from the field in the earlier mentioned pilot project [53]. The comparison results are shown in Table 2.1-1 with the t-test results indicating whether the travel times between the field data and simulation were statistically identical.

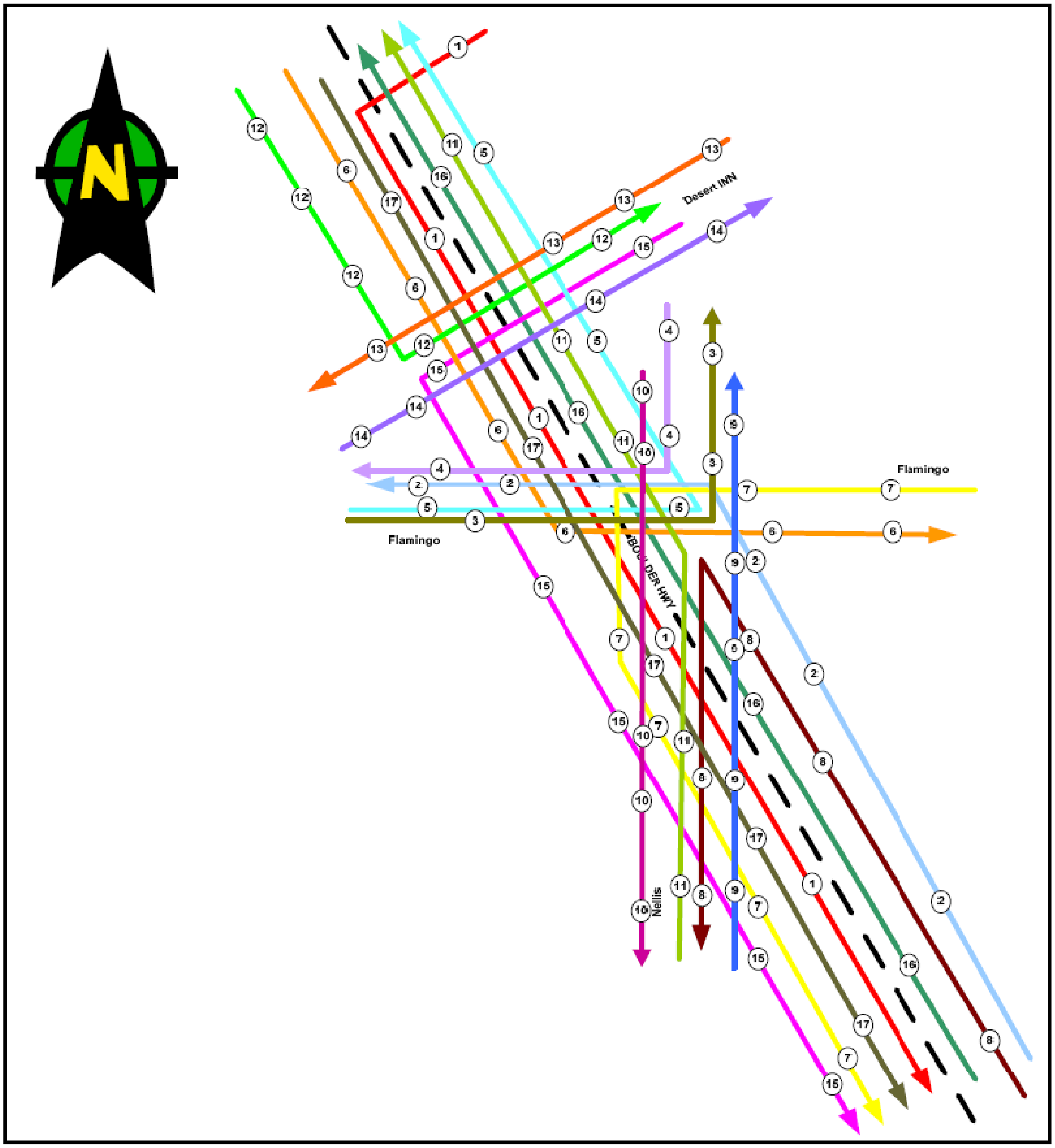


Figure 2.1-8 Test Routes for Travel Time Comparison

Table 2.1-1 Travel Time Comparison between Field Data and Simulation

Route	Data	Mean	Standard Deviation	Statistically the Same?
1	Field	377.7	8.1	N
	Simulation	410.1	50.8	
2	Field	534.3	601.6	Y
	Simulation	155.8	55.5	
3	Field	123.0	112.3	Y
	Simulation	105.5	8.4	
4	Field	14.3	1.5	N
	Simulation	43.2	29.6	
5	Field	285.0	4.6	Y
	Simulation	272.7	7.6	
6	Field	428.7	81.5	Y
	Simulation	387.6	21.9	
7	Field	353.7	113.0	Y
	Simulation	276.4	54.6	
8	Field	193.7	82.1	Y
	Simulation	153.7	45.0	
9	Field	103.3	64.4	Y
	Simulation	37.1	36.5	
10	Field	15.0	4.6	N
	Simulation	52.4	50.6	
11	Field	270.3	8.1	Y
	Simulation	251.5	12.8	
12	Field	70.0	16.8	N
	Simulation	137.4	20.9	
13	Field	168.3	24.0	Y
	Simulation	155.0	31.1	
14	Field	211.7	102.0	Y
	Simulation	159.3	33.0	
15	Field	332.0	6.6	N
	Simulation	418.3	57.1	
16	Field	368.3	78.1	Y
	Simulation	318.3	53.6	
17	Field	339.0	32.0	N
	Simulation	375.5	56.5	

Note: 1. Routes were sorted based on field standard deviation; 2. Number of travel time runs from the field was 3 (weekday p.m. peak), and number of simulation runs was 10.

From Table 2.1-1, 11 out of 17 routes had statistically identical results between field data and simulation, suggesting the model was calibrated fairly well considering the significant variations from the field data. It should be noted that exhaustive model calibration might not be necessary as the conditions would change during actual simulation modeling, and the results would be compared by the relative difference.

2.2 Simulation Settings

2.2.1 Simulation Scenarios

Table 2.2-1 shows all the simulation scenarios analyzed. There were a total of 27 scenarios generated from seven cases with each case representing a specific traffic flow and network condition. As can be seen, these seven cases covered a wide range of conditions most likely to be encountered in a real world operation. Scenarios associated with the base case represented the existing network where only the traffic demand levels vary. Case 2 and 3 were associated with special events and nearby land developments where a significantly high demand occurred only at a specific location and for specific traffic movements. Scenarios associated with Cases 4 and 5 represented incident conditions at nearby arterials where significant traffic diversion to the subject arterial occurred, causing traffic demand surge in one travel direction. Scenarios associated with Cases 6 and 7 represented different levels of detector failures. Each case included five demand levels except for Cases 2 and 3. For these two cases, the demands had already significantly exceeded the capacities, thus the analyses of other demand levels were no longer necessary. The last column indicates the base case scenario against which the comparisons were made. One of the cases originally planned but not included in this section was associated with preemption. This was due to the lack of a function in the current SCATSIM to directly recognize preemption calls from VISSIM simulation software.

Table 2.2-1 Simulation Scenarios

	Case Description	Scenario ID	Scenario Description	Base Scenario
1	001 Base Case (Existing Network)	001-1	Low Demand (50% of PM Peak Demand)	001-3
2		001-2	Medium Low Demand (75% of PM Peak Demand)	001-3
3		001-3	Medium Demand (100% of PM Peak Demand)	-
4		001-4	Medium High Demand (120% of PM Peak Demand)	001-3
5		001-5	High Demand (150% of PM Peak Demand)	001-3
6	002 Special Event	002	100% increase of Eastbound at Flamingo Rd	001-3
7	003 New development	003	100% increase of related movements at Harmon Ave	001-3
8	004 Directional Flow 1 (Peak for SB Boulder)	004-1	Low Demand	001-1
9		004-2	Medium Low Demand	001-2
10		004-3	Medium Demand	001-3
11		004-4	Medium High Demand	001-4
12		004-5	High Demand	001-5
13	005 Directional Flow 2 (Peak for NB Boulder)	005-1	Low Demand	001-1
14		005-2	Medium Low Demand	001-2
15		005-3	Medium Demand	001-3
16		005-4	Medium High Demand	001-4
17		005-5	High Demand	001-5
18	006 Detector Fail (NB detectors fail)	006-1	Low Demand	001-1
19		006-2	Medium Low Demand	001-2
20		006-3	Medium Demand	001-3
21		006-4	Medium High Demand	001-4
22		006-5	High Demand	001-5
23	007 Detector Fail (Major Street detectors Fail)	007-1	Low Demand	001-1 & 006-1
24		007-2	Medium Low Demand	001-2 & 006-2
25		007-3	Medium Demand	001-3 & 006-3
26		007-4	Medium High Demand	001-4 & 006-4
27		007-5	High Demand	001-5 & 006-5

2.2.2 Measures of Effectiveness (MOEs)

Six MOEs were used for the evaluation: Delay, Stopped Delay, Stops, Speed, Queue Length, and Travel Time. According to VISSIM's user manual, the definitions for the above six MOEs are provided below:

- **Delay**: Average total delay per vehicle (in seconds). Delay is computed for every vehicle completing the travel time section by subtracting the theoretical (ideal) travel time from the real travel time. For Network Level, travel time section is whole simulation network. For Node Level, travel time section is created automatically as a combination of new travel time measurements from all possible upstream starting points to the node exit point of the respective turning relation.

- **Stopped Delay**: Average standstill time per vehicle (in seconds).
- **Stops**: Average number of stops per vehicle, not including stops at transit stops or in parking lots.
- **Speed**: Average speed (in miles per hour).
- **Queue Length**: Average Queue Length (in feet). The node evaluation places a queue counter on every edge (movement) found inside the node. It is placed at the position of the signal head or priority rule stop line that is the closest one upstream to the node boundary on the respective edge.
- **Travel Time**: Average travel time across a travel time section for all vehicles that complete the travel time section (in seconds).

These MOEs were reported and compared at the three levels: Network Level, Node Level and Route Level.

2.2.3 Simulation Scheme

Analyses using microscopic traffic simulation models require multiple runs to duplicate a traffic condition and to obtain reliable statistics. As described above, this can be achieved by either conducting multiple simulation runs or having a single run with a longer simulation time which would involve multiple traffic demand representations. Because SCATS has a memory feature that would start a control environment based on past events and performance, this study adopted the single long run option whose advantages have already been demonstrated in previous studies. As noted, single simulation run included multiple peaks with each peak resembling a regular simulation run. However, between each peak, warm-up time and clearance times were added to fill out the network and clear out the residual vehicles by the end of each peak (as shown in Figure 2.2-1). MOEs were reported for the duration between the end of system warm-up time and clearance time.

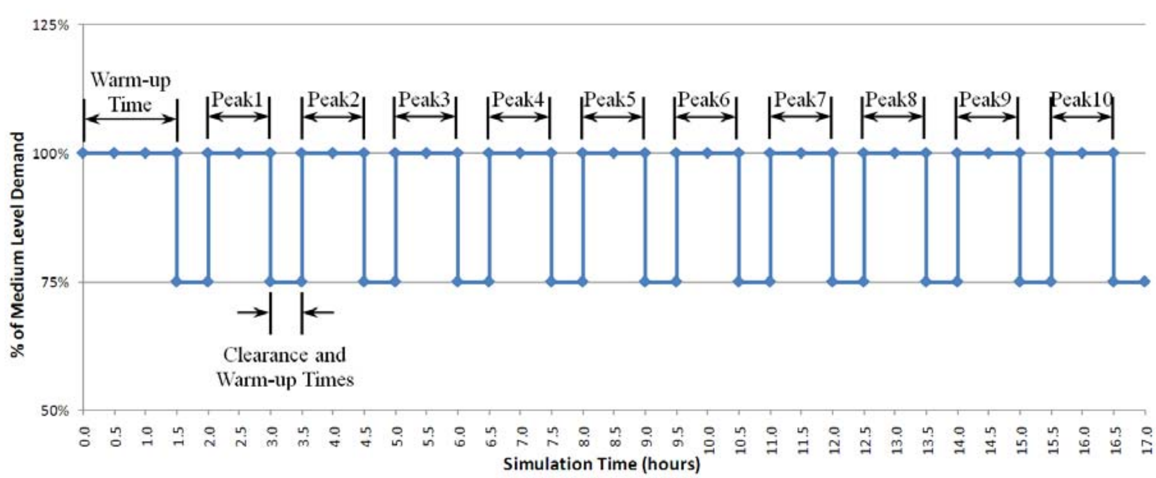


Figure 2.2-1 Traffic Demand Profile in Simulation

For traffic demand at Low, Medium Low, and Medium levels, 75% of peak volume was used to clear out and warm-up the network. But for the Medium High and High level demand situations, 30% of peak volume was used to clear out the residual vehicles in the network. Selecting 30% of peak volume during clearance time was to ensure most vehicles can be cleared out by the end of peak, so that each peak would start at the same demand level. An example for Node Level MOEs' at High demand level indicating MOEs in different peaks are very close to each other (as Figure 2.2-2 shows). It suggests that there were no remaining vehicles from each peak affecting subsequent peaks' simulation results.

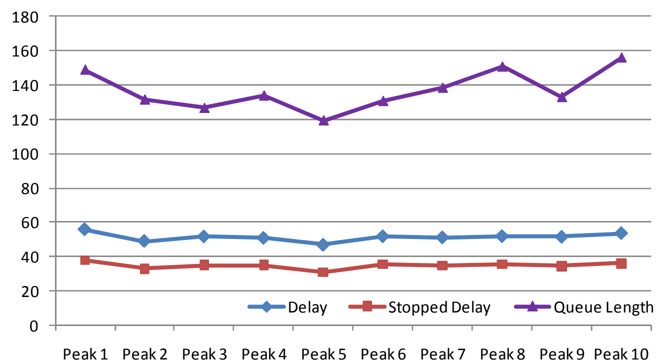


Figure 2.2-2 Simulation Results in Different Peaks

2.2.4 Hierarchy of Analyses

Figure 2.2-3 shows the hierarchy of the simulation analyses, including the performance evaluation at three different levels: the network level, the node/intersection level, and the route level.

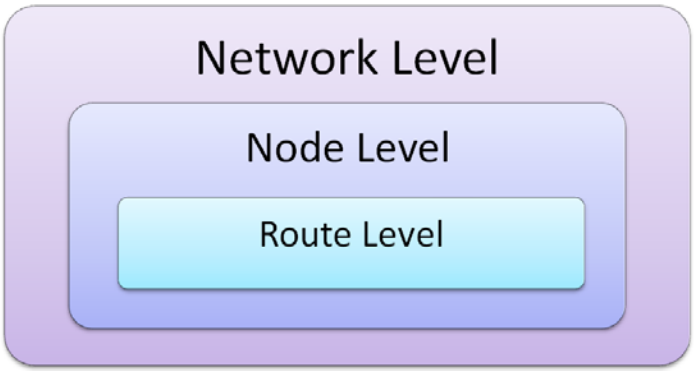


Figure 2.2-3 Hierarchy of Analysis

The Network Level comparison focused on the performance of the entire system, which would not only evaluates the main street performance, but also the side street performance. The Node Level comparison focused on the performances at the individual intersections. The comparison results would reveal whether SCATS system can provide more efficient and balanced services to all movements at each intersection. The experimental network included a total of 10 nodes as shown in Table 2.2-2 and Figure 2.2-4.

Table 2.2-2 List of Nodes in the Study Network

Node ID	Main Street	Side Street
Node 1	Boulder Hwy	SR-95 SB
Node 2	Boulder Hwy	SR-95 NB
Node 3	Boulder Hwy	Desert Inn Rd
Node 4	Boulder Hwy	Indios Ave
Node 5	Boulder Hwy	Flamingo Rd
Node 6	Boulder Hwy	Nellis Blvd
Node 7	Boulder Hwy	Harmon Ave
Node 8	Boulder Hwy	Tropicana Ave
Node 9	Flamingo Rd	Nellis Blvd
Node 10	Flamingo Rd	Perry St

The Route Level comparison examined the performance at all the major travel routes, which would better represent the drivers' perspective. For example, drivers may not well perceive the overall system delay and stops, but they could experience the performance of a driving route, especially the main-street routes. A total of 17 routes were identified to cover all the major routes within the study network. These routes included not only the arterial through routes, but also the routes that involved major turning movements entering or exiting the arterial (shown in Figure 2.2-4). These same 17 routes were also used for calibrating the VISSIM model based on field data.

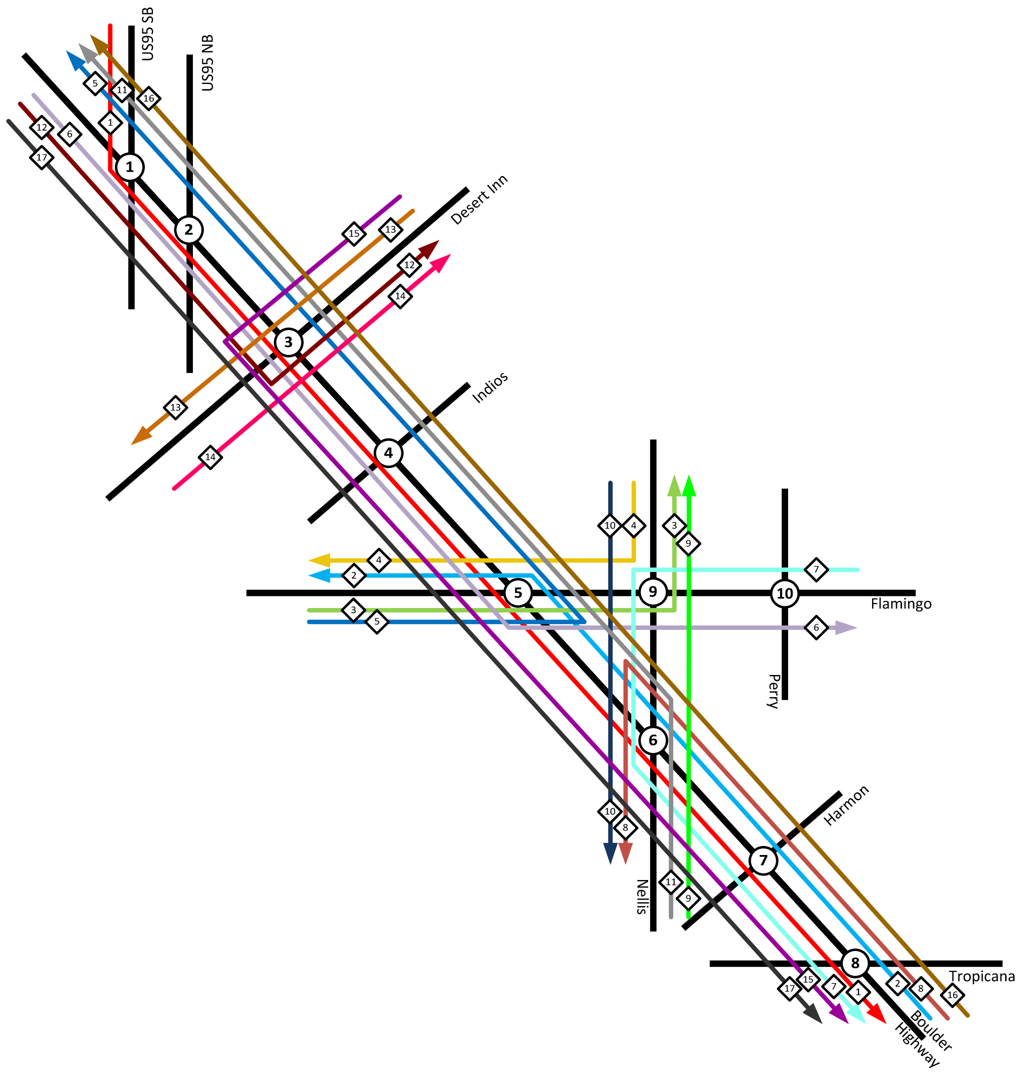


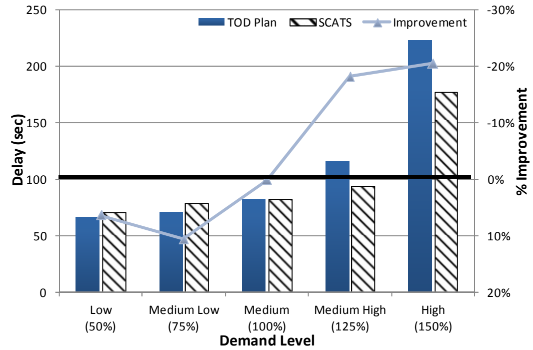
Figure 2.2-4 List of Nodes and Travel Routes in the Study Network

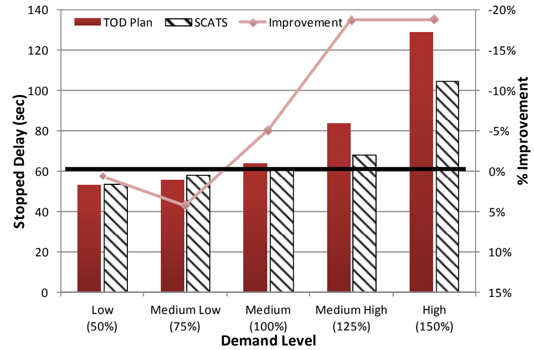
2.3 *Analysis Results*

2.3.1 Case 001 – Base Network

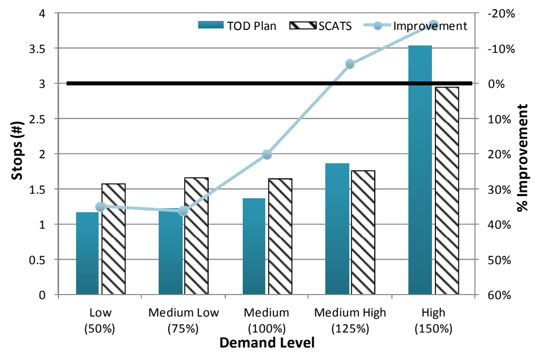
Overall Performance

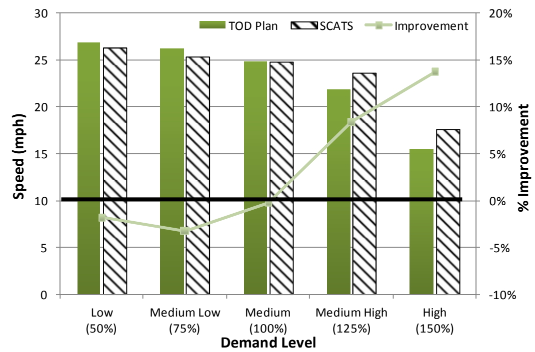
The base case network (Case 001) was established based on the original Boulder Hwy network. Five simulation scenarios representing different levels of traffic demand were derived based on this base case network. The intention of this case analysis was to evaluate how traffic demand level may affect SCATS performance, so that guidelines can be developed on the applicability of SCATS based on traffic demand levels. The detailed MOEs for the two control systems (i.e., TOD and SCATS) are illustrated in Figure 2.3-1 to Figure 2.3-3.





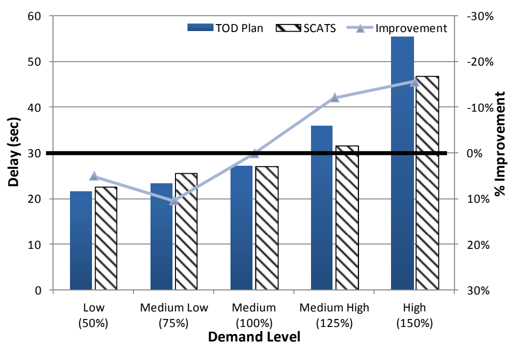
(a) (b)

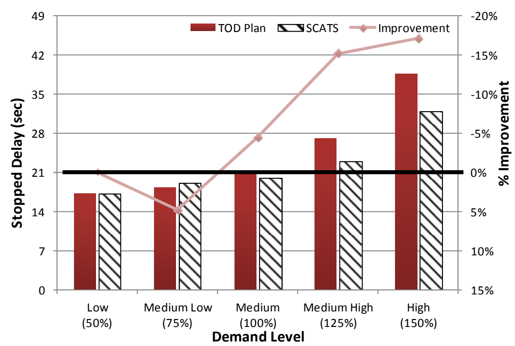




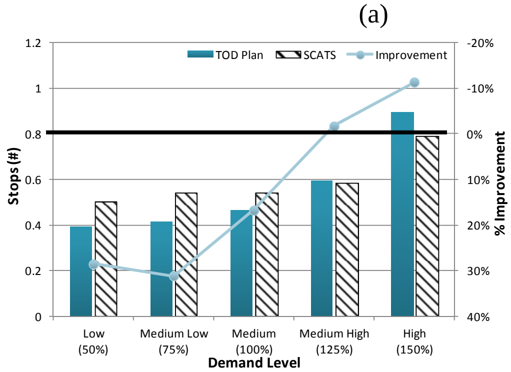
(c) (d)

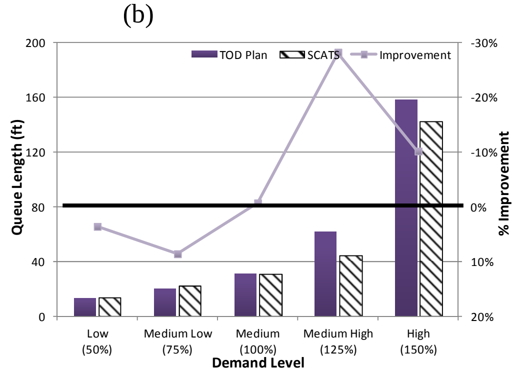
Figure 2.3-1 SCATS Performance for Network Level MOEs





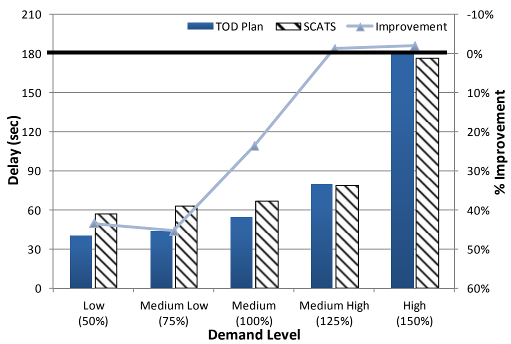
(a) (b)



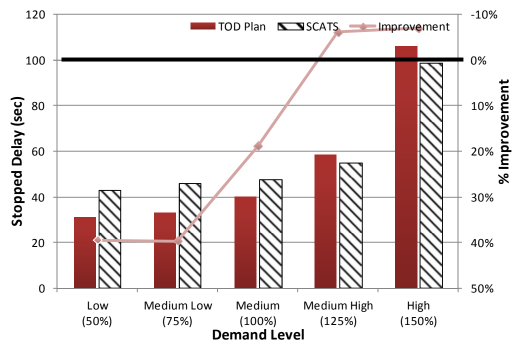


(c) (d)

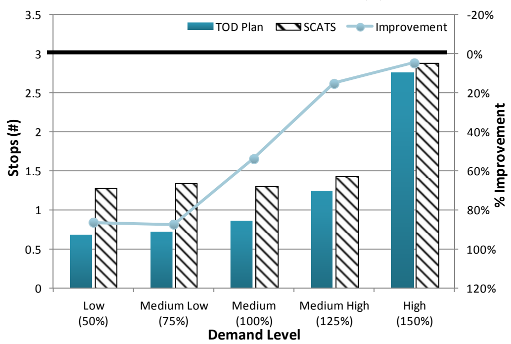
Figure 2.3-2 SCATS Performance for Node Level MOEs



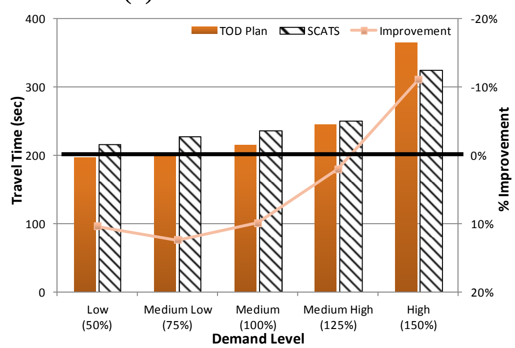
(a)



(b)



(c)



(d)

Figure 2.3-3 SCATS Performance for Route Level MOEs

In the above figures, bars represent the actual MOEs values. The curved lines represent the relative improvements (in percent) of SCATS over TOD. The magnitude of the improvement is indicated by the secondary Y-axis (right side Y-axis). The thick dark horizontal lines in the figures show the 0% improvement, i.e., any points above this line meaning SCATS improved over TOD, while any points below the line meaning TOD plan worked better. Different colors were used to illustrate different MOEs and the details are included in Table 2.3-1.

Table 2.3-1 Colors Used for Different MOEs

MOEs	Color
Delay	Blue
Stopped Delay	Red
Stops	Cyan
Speed	Green
Queue	Purple
Travel Time	Orange

From Figure 2.3-1 (Network Level) and Figure 2.3-2 (Node Level), SCATS system showed better performance at the higher demand levels. Since the MOEs included all the vehicles entered the system, the "shoulder" effect (i.e., before and after the peak demand) was adequately reflected in the results. Therefore, the better performance of SCATS at the higher demand levels indicated SCATS's superiority in handling pre and post congestions, i.e., for congested systems, SCATS was more effective for delaying the onset of congestion and for quick recovery from congestion. As the 100% demand level corresponded to an at-capacity condition at the key intersections, it suggests that SCATS would be beneficial when the demand exceeds capacity. When traffic demand is low, TOD control can generally achieve better performance at system and intersection levels.

From Figure 3.1-3 (Route Level), SCATS system showed similar trends, but the improvement at the higher demand levels were not so obvious. In fact, the number of stops increased with SCATS under all demand levels, which may suggest that SCATS tended to provide a balanced service to all the traffic movements in the system, but not particularly focused on the routes level progression as what TOD plans did. In TOD plan operation, progression on the main street routes was usually given higher priority while individual minor movements may have suffered.

Detailed MOEs and Analyses

- **Summary of Network Level MOEs**

The statistical analyses results for the Network Level MOEs are included in Table 2.3-2.

Table 2.3-2 Network Level MOEs (Base Case)

Deland Level	MOEs	TOD Plan	SCATS	% Change
Low	Delay	66.7	71.0	6.4%
	Stopped Delay	53.4	53.7	0.6%
	Stops	1.2	1.6	35.0%
	Speed	26.8	26.3	-1.8%
Medium Low	Delay	71.0	78.5	10.6%
	Stopped Delay	55.8	58.2	4.2%
	Stops	1.2	1.7	36.2%
	Speed	26.2	25.3	-3.2%
Medium	Delay	82.8	82.9	0.1%
	Stopped Delay	63.7	60.5	-5.1%
	Stops	1.4	1.6	20.2%
	Speed	24.8	24.8	-0.2%
Medium High	Delay	115.2	94.3	-18.1%
	Stopped Delay	83.9	68.2	-18.7%
	Stops	1.9	1.8	-5.4%
	Speed	21.8	23.6	8.4%
High	Delay	223.1	177.5	-20.5%
	Stopped Delay	128.7	104.5	-18.8%
	Stops	3.5	2.9	-16.8%
	Speed	15.5	17.6	13.7%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

As the above table shows, all four Network Level MOEs were improved with SCATS system under the Medium High and High demand levels; however, traditional TOD control performed better under the lower demand levels. Due to VISSIM's limitation on reporting simulation results, Network Level MOEs could not be reported by time intervals. Therefore, the conclusions for Network Level MOEs' comparison results were mainly made based on anecdotal evidences.

- **Statistical Analysis for Node Level MOEs**

The Node Level statistical analyses are presented in Table 2.3-3 to Table 2.3-7. The t-statistical test was used to compare all the MOEs between the two control types. The statistics (mean and standard deviation) of the MOEs were obtained from each simulation run that included 10 emulated peak hour traffic flows.

The Node Level comparison revealed that SCATS improved "Stopped Delay" in 30 out of 55 occasions, while TOD plan achieved fewer "Stops" in most cases. No significant difference was noticed for the other two MOEs between the two control systems.

Table 2.3-3 Node Level MOEs (Base Case)

	MOEs	TOD Plan	SCATS	% Change
Low	Delay	21.6	22.7	5.1%
	Stopped Delay	17.3	17.3	0.0%
	Stops	0.39	0.50	28.5%
	Queue	13.3	13.8	3.6%
Medium Low	Delay	23.2	25.6	10.5%
	Stopped Delay	18.2	19.1	4.8%
	Stops	0.41	0.54	31.2%
	Queue	20.3	22.1	8.7%
Medium	Delay	27.1	27.2	0.2%
	Stopped Delay	20.9	20.0	-4.4%
	Stops	0.46	0.54	16.7%
	Queue	31.0	30.7	-0.7%
Medium High	Delay	35.9	31.5	-12.0%
	Stopped Delay	27.1	23.0	-15.2%
	Stops	0.59	0.58	-1.8%
	Queue	61.8	44.5	-28.1%
High	Delay	55.4	46.8	-15.5%
	Stopped Delay	38.6	32.0	-17.1%
	Stops	0.89	0.79	-11.2%
	Queue	157.9	142.1	-10.0%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

Table 2.3-4 t-test Significance for Node Level Delay (Base Case)

	Low	Medium Low	Medium	Medium High	High
Node 1	S	S	S	S	S
Node 2	T	T	T	T	T
Node 3	S	S	S	T	T
Node 4	T	T	T	S	S
* Node 5	T	T	T	S	S
* Node 6	T	T	T	S	S
Node 7	S	S	N	S	N
Node 8	N	T	S	S	T
* Node 9	S	S	S	S	S
Node 10	T	T	T	T	T
Average	T	T	N	S	S

* Node with '*' are the critical intersections in the Triangle Area.

** "T" represents TOD Plan is significantly better than SCATS; "S" represents SCATS is significantly better than TOD plan; "N" represents no significant difference between the two controls.

Table 2.3-5 t-test Significance for Node Level Stopped Delay (Base Case)

	Low	Medium Low	Medium	Medium High	High
Node 1	S	S	S	S	S
Node 2	N	N	N	T	T
Node 3	S	S	S	N	T
Node 4	T	T	N	S	S
* Node 5	T	T	N	S	S
* Node 6	T	T	T	S	S
Node 7	S	S	S	S	S
Node 8	S	N	S	S	T
* Node 9	S	S	S	S	S
Node 10	T	T	T	T	T
Average	N	T	S	S	S

* Node with '*' are the critical intersections in the Triangle Area.

Table 2.3-6 t-test Significance for Node Level Stops (Base Case)

	Low	Medium Low	Medium	Medium High	High
Node 1	S	N	N	T	S
Node 2	T	T	T	T	T
Node 3	T	T	T	T	T
Node 4	T	T	T	T	S
* Node 5	T	T	T	N	S
* Node 6	T	T	T	S	S
Node 7	T	T	T	T	T
Node 8	T	T	N	T	T
* Node 9	S	S	S	S	S
Node 10	S	S	S	S	S
Average	T	T	T	N	S

* Node with '*' are the critical intersections in the Triangle Area.

Table 2.3-7 t-test Significance for Node Level Queue (Base Case)

	Low	Medium Low	Medium	Medium High	High
Node 1	N	N	N	S	S
Node 2	N	T	T	T	N
Node 3	S	S	S	T	T
Node 4	T	T	S	S	S
* Node 5	T	T	T	N	S
* Node 6	T	T	N	S	S
Node 7	N	N	T	T	T
Node 8	S	T	S	N	T
* Node 9	S	S	S	S	S
Node 10	T	T	T	T	T
Average	T	T	N	S	S

* Node with '*' are the critical intersections in the Triangle Area.

- **Statistical Analysis for Route Level MOEs**

The Route Level MOEs and the statistical analyses results are presented in Table 2.3-8 to Table 2.3-12.

Table 2.3-8 Route Level MOEs (Base Case)

	MOEs	TOD Plan	SCATS	% Change
Low	Delay	40.2	57.6	43.5%
	Stopped Delay	30.9	43.1	39.5%
	Stops	0.68	1.27	86.4%
	Travel Time	195.8	216.1	10.4%
Medium Low	Delay	43.7	63.5	45.4%
	Stopped Delay	33.0	46.1	39.6%
	Stops	0.71	1.34	87.4%
	Travel Time	202.5	227.7	12.4%
Medium	Delay	54.2	67.0	23.7%
	Stopped Delay	40.1	47.6	18.9%
	Stops	0.85	1.31	53.7%
	Travel Time	215.2	236.5	9.9%
Medium High	Delay	79.9	79.0	-1.2%
	Stopped Delay	58.4	54.9	-6.1%
	Stops	1.24	1.43	15.2%
	Travel Time	245.2	250.2	2.1%
High	Delay	180.4	176.9	-1.9%
	Stopped Delay	106.1	98.8	-6.9%
	Stops	2.76	2.88	4.5%
	Travel Time	364.6	324.3	-11.1%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

Table 2.3-9 t-test Significance for Route Level Delay (Base Case)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	T	S	S
Route 2	T	T	T	T	N
Route 3	S	S	S	S	T
Route 4	S	S	S	N	T
Route 5	S	S	S	T	T
Route 6	T	T	N	T	S
Route 7	S	S	N	S	S
Route 8	T	T	T	N	N
Route 9	S	S	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	T	T
Route 13	N	N	S	T	T
Route 14	S	S	N	T	T
Route 15	T	T	T	S	S
* Route 16	T	T	T	T	T
* Route 17	T	T	T	S	S
Average	T	T	T	N	N

* Route with * represents through route.

Table 2.3-10 t-test Significance for Route Level Stopped Delay (Base Case)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	T	S	S
Route 2	T	T	N	S	N
Route 3	S	S	S	S	T
Route 4	S	S	S	N	T
Route 5	S	S	S	N	N
Route 6	T	T	T	T	S
Route 7	S	S	N	S	S
Route 8	T	N	N	S	N
Route 9	S	S	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	T	T
Route 13	N	S	S	T	T
Route 14	S	S	N	T	T
Route 15	T	T	T	S	S
* Route 16	T	T	T	T	N
* Route 17	T	T	T	S	S
Average	T	T	T	S	S

* Route with * represents through route.

Table 2.3-11 t-test Significance for Route Level Stops (Base Case)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	T	S	S
Route 2	T	T	T	T	N
Route 3	S	S	N	N	T
Route 4	N	S	N	T	T
Route 5	T	T	T	T	T
Route 6	T	T	T	T	S
Route 7	S	S	S	S	S
Route 8	N	N	T	N	N
Route 9	S	S	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	T	T
Route 13	T	T	T	T	T
Route 14	T	T	T	T	T
Route 15	T	T	T	S	S
* Route 16	T	T	T	T	T
* Route 17	T	T	T	N	S
Average	T	T	T	T	N

* Route with * represents through route.

Table 2.3-12 t-test Significance for Route Level Travel Time (Base Case)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	T	S	S
Route 2	T	T	T	T	N
Route 3	S	S	S	S	T
Route 4	N	N	S	N	T
Route 5	S	S	S	T	T
Route 6	T	N	N	T	S
Route 7	S	S	N	T	T
Route 8	T	T	T	N	N
Route 9	S	S	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	T	T
Route 13	N	N	N	T	T
Route 14	S	S	N	N	T
Route 15	T	T	T	S	S
* Route 16	T	T	T	T	T
* Route 17	T	T	T	S	S
Average	T	T	T	T	S

* Route with * represents through route.

In general, TOD control produced better Route Level performances than SCATS under most demand levels; however, SCATS showed much improved performance for some routes under the high demand levels, including the arterial through routes.

2.3.2 Case 002 – Special Events

Special events such as major sports and conventions can cause a sudden surge of traffic demands at a particular intersection. This case was specifically designed to simulate such special event occasions and find out how SCATS would react to such abnormal traffic conditions. The case with 100% increase (double the demand) on the eastbound approach of the Boulder Hwy/Flamingo Rd intersection was used for the analyses. As mentioned earlier in Section 2.2.1, the significant increase in traffic demands may cause some movements far exceeding their capacities, therefore, only the Medium demand level was simulated.

Summary of Network Level MOEs

Table 2.3-13 includes all the Network Level MOEs for this case. It can be observed that SCATS only showed better performance for "Stopped Delay", while TOD plan performed better in all other three MOEs. However, by examining the absolute values of the MOEs, there was practically no difference between the two control types.

Table 2.3-13 Network Level MOEs (Case: Special Event)

	TOD Plan	SCATS	% Change
Delay	83.9	87.3	4.0%
Stopped Delay	64.3	61.0	-5.1%
Stops	1.39	1.76	26.9%
Speed	24.6	24.3	-1.3%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

Besides the direct comparison between SCATS and TOD plan, another comparison scheme was also made so as to verify the applicability and robustness of SCATS in handling Special Events (See Table 2.3-14). In the table, SCATS' improvements over TOD under Base Case and Special Event Case were compared. This comparison would reveal whether SCATS can better handle special events.

Table 2.3-14 Effectiveness of SCATS in Handling Special Events

	SCATS' Improvement Base Case (001)	SCATS' Improvement Special Event Case (002)	Comparison Between (002) and (001)
Delay	0.1%	4.0%	**WORSE**
Stopped Delay	-5.1%	-5.1%	**SAME**
Stops	20.2%	26.9%	**WORSE**
Speed	-0.2%	-1.3%	**WORSE**

In Table 2.3-14, "WORSE" means SCATS system did not perform as effectively as the Base Case. Due to the lack of report function in VISSIM, the above conclusion was also generated based on anecdotal evidence instead of statistical results.

Statistical Analysis for Node Level MOEs

Table 2.3-15 summarizes the Node Level MOEs and comparison the results, and Table 2.3-16 includes the detailed t-test results.

Table 2.3-15 Node Level MOEs (Case: Special Event)

	TOD Plan	SCATS	% Change
Delay	29.0	29.5	1.7%
Stopped Delay	22.3	21.1	-5.7%
Stops	0.48	0.60	24.8%
Queue	32.9	38.7	17.7%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

Table 2.3-16 t-test Significance for Node Level MOEs (Case: Special Event)

	Delay	Stopped Delay	Stops	Queue
Node 1	S	S	T	S
Node 2	N	S	T	S
Node 3	S	S	T	S
Node 4	T	T	T	S
*** Node 5**	T	T	T	T
*** Node 6**	T	T	T	T
Node 7	N	S	T	T
Node 8	S	S	N	S
*** Node 9**	S	S	S	S
Node 10	T	T	S	T
Average	T	S	T	T

* Node with '*' are the critical intersections in the Triangle Area.

As can be seen, SCATS only showed better performance in "Stopped Delay". TOD plan showed better performance in other three MOEs. For the triangle area intersections, TOD plan showed better performance for the intersections of Boulder Hwy/Flamingo Rd and Boulder Hwy/Nellis Blvd, while SCATS showed better performance at Flamingo Rd/ Nellis Blvd.

Statistical Analysis for Route Level MOEs

Table 2.3-17 summarizes the Route Level MOEs and comparison results, and the detailed t-test results are shown in Table 2.3-18Table 2.3-18.

Table 2.3-17 Route Level MOEs (Case: Special Event)

	TOD Plan	SCATS	% Change
Delay	61.1	77.8	27.4%
Stopped Delay	45.4	53.4	17.5%
Stops	0.95	1.49	56.0%
Travel Time	227.7	249.0	9.4%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

The result indicated that TOD performed better for the "Special Event" case at the Route Level in most occasions. For the two through routes, all four MOEs revealed that TOD plan performed better than SCATS (See Table 2.3-18).

Table 2.3-18 t-test Significance for Route Level MOEs (Case: Special Event)

	Delay	Stopped Delay	Stops	Travel Time
Route 1	T	T	T	T
Route 2	T	N	T	T
Route 3	T	T	T	T
Route 4	S	S	S	S
Route 5	T	T	T	T
Route 6	S	S	T	S
Route 7	S	S	S	S
Route 8	T	N	T	T
Route 9	S	S	S	S
Route 10	T	T	T	T
Route 11	T	T	T	T
Route 12	T	T	T	T
Route 13	N	N	T	T
Route 14	N	N	T	S
Route 15	T	T	T	T
* Route 16	T	T	T	T
* Route 17	T	T	T	T
Average	T	T	T	T

* Route with * represents through route.

2.3.3 Case 003 – New Development

A major new land use development near the network may significantly increase the traffic demands for particular intersection movements. Traditional TOD plan may not well adapt such traffic demand increases without a major re-timing effort, while an adaptive signal control system could benefit in such conditions. Such a new development case was established by increasing 100% for the related movements at the intersection of Boulder Hwy and Harmon Ave (as Figure 2.3-4 shown).

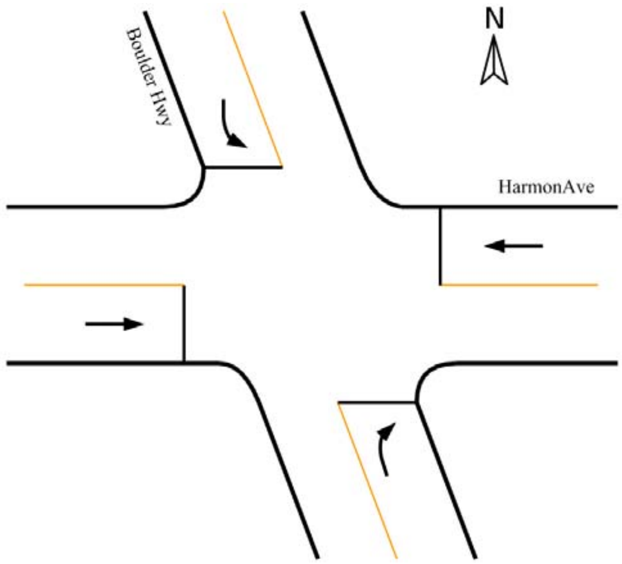


Figure 2.3-4 Direction of Traffic Demand Incensement

Summary of Network Level MOEs

Table 2.3-19 includes the Network Level MOEs for TOD control and SCATS system. It can be seen that SCATS improved slightly over TOD in three MOEs: Delay, Stopped Delay, and Speed, but showed increase in Stops.

Table 2.3-19 Network Level MOEs (Case: New Development)

	TOD Plan	SCATS	% Change
Delay	81.1	80.5	-0.8%
Stopped Delay	62.4	57.9	-7.2%
Stops	1.35	1.65	22.4%
Speed	24.7	24.8	0.4%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

Similarly, a comparison with the Base Case was made to identify the effectiveness of SCATS in handling New Development case, and the results are shown in Table 2.3-20.

Table 2.3-20 Effectiveness of SCATS in Handling New Development

	SCATS' Improvement for The Base Case (001)	SCATS' Improvement in This Case (003)	The Comparison Between (001) and (003)
Delay	0.1%	-0.8%	**BETTER**
Stopped Delay	-5.1%	-7.2%	**BETTER**
Stops	20.2%	22.4%	**WORSE**
Speed	-0.2%	0.4%	**BETTER**

The results indicated that SCATS system was generally effective in handling new development scenarios where significant traffic growth occurred near the network. These were mainly reflected by the improved performance in Delay, Stops, and Speed.

Statistical Analysis for Node Level MOEs

Table 2.3-21 is a summary of the Node Level MOEs, in which SCATS showed improvement in "Delay", "Stopped Delay", and "Queue".

Table 2.3-21 Node Level MOEs (Case: New Development)

	TOD Plan	SCATS	% Change
Delay	29.1	29.0	-0.2%
Stopped Delay	22.4	20.9	-6.7%
Stops	0.48	0.59	22.0%
Queue	30.9	29.8	-3.7%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

Results from the t-test analyses for the Node Level MOEs are shown in Table 2.3-22. The results indicated that SCATS generally improved over TOD on two major MOEs: "Stopped Delay" and "Queue". However, TOD control still showed fewer "Stops" than SCATS.

Table 2.3-22 t-test Significance for Node Level MOEs (Case: New Development)

	Delay	Stopped Delay	Stops	Queue
Node 1	S	S	T	S
Node 2	N	S	T	S
Node 3	S	S	T	S
Node 4	N	N	T	S
* Node 5	T	T	T	T
* Node 6	T	T	T	T
** Node 7	N	S	T	S
Node 8	S	S	T	N
* Node 9	S	S	S	S
Node 10	T	T	S	T
Average	N	S	T	S

* Node with '*' are the critical intersections in the Triangle Area.

** Node 7 is Boulder Hwy/Harmon intersection, near which the new development was assumed.

Statistical Analysis for Route Level MOEs

Table 2.3-23 summarizes the Route Level MOEs and comparison results, and detailed t-test results are shown in Table 2.3-24.

Table 2.3-23 Route Level MOEs (Case: New Development)

	TOD Plan	SCATS	% Change
Delay	53.3	66.6	25.0%
Stopped Delay	39.4	46.9	19.2%
Stops	0.83	1.30	55.9%
Travel Time	214.3	238.1	11.1%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

Table 2.3-24 t-test Significance for Route Level MOEs (Case: New Development)

	Delay	Stopped Delay	Stops	Travel Time
Route 1	T	T	T	T
Route 2	T	N	T	T
Route 3	S	S	S	S
Route 4	S	S	S	N
Route 5	S	S	T	N
Route 6	T	T	T	T
Route 7	T	T	S	T
Route 8	T	S	T	T
Route 9	S	S	N	S
Route 10	T	T	T	T
Route 11	T	T	T	T
Route 12	T	T	T	T
Route 13	N	S	T	N
Route 14	N	N	T	S
Route 15	T	T	T	T
* Route 16	T	T	T	T
* Route 17	T	T	T	T
Average	T	T	T	T

* Route with * represents through route.

The Statistical result indicated that for the Route Level MOEs, TOD plan showed better performance in most occasions, especially for two through routes, where all four MOEs showed significantly better results than SCATS.

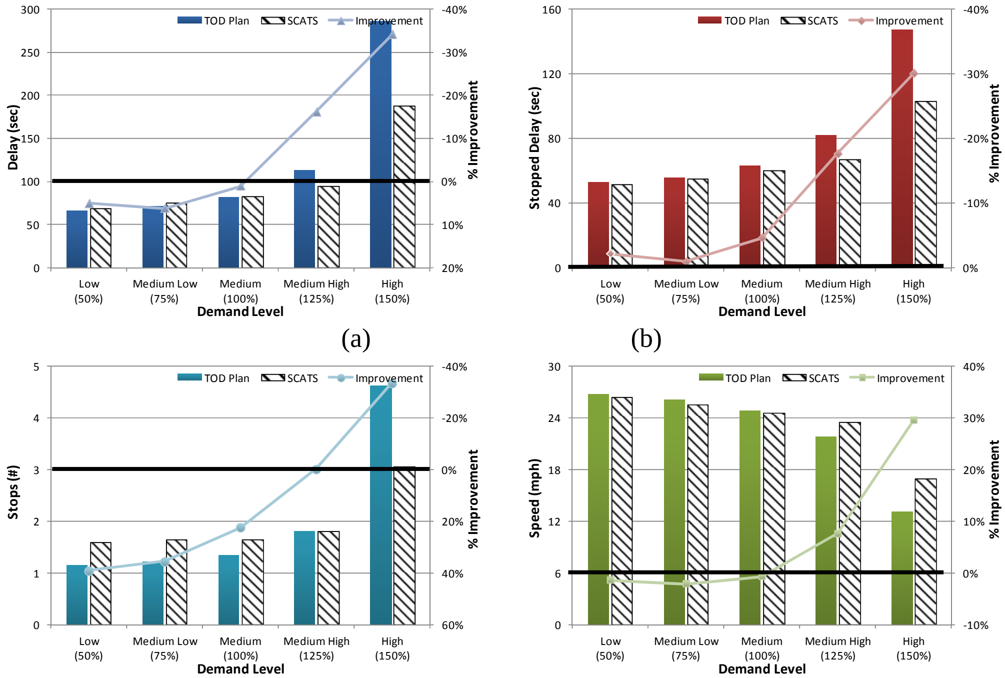
In general, SCATS showed better performance under the case of "New Development" at the Network and Node levels, but no further improvement was shown at the Route level.

2.3.4 Case 004 – Directional Flow-1

Overall Performance

Directional Flow cases represent incident conditions at nearby arterials where significant traffic diversion to the subject arterial would occur, causing demand surge in one travel direction. Besides, directional flow is also a common phenomenon in most urban commute corridors. Directional flow is characterized by the volume of one direction being significantly higher than the other direction. Signal progression is generally favored for the higher volume direction. The progression for the lower volume direction often results in more stops. This case was established to testify whether SCATS could automatically detect the directional traffic flow pattern and provide a better signal progression for the peak direction. The peak flow direction for the Directional Flow-1 Case was the southbound on Boulder Hwy.

Figure 2.3-5 to Figure 2.3-7 illustrate the three levels MOEs of TOD and SCATS system.

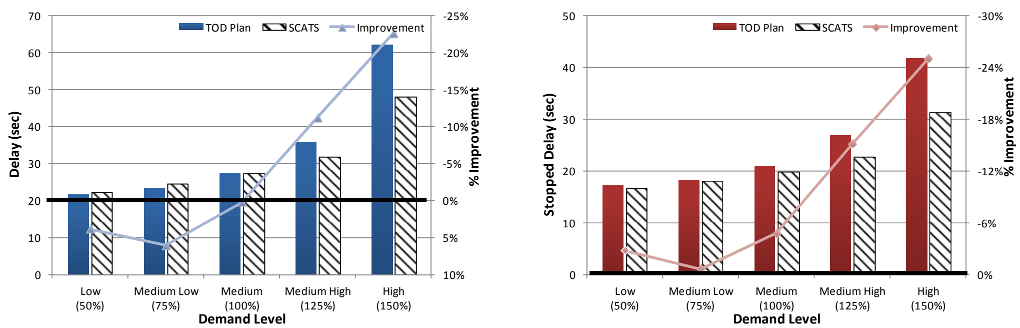


(a) (b)

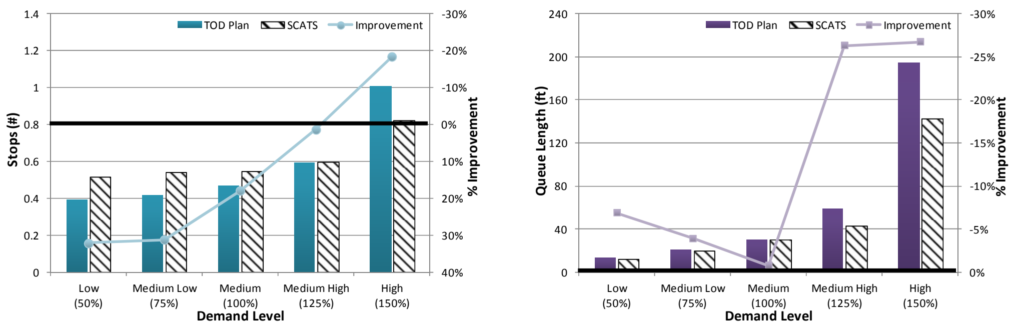
(c) (d)

Figure 2.3-5 SCATS Performance for Network Level MOEs

For Network Level MOEs, it can be seen that SCATS performed better at High demand level. All four Network Level MOEs showed improvement when the demand was higher than the capacity.

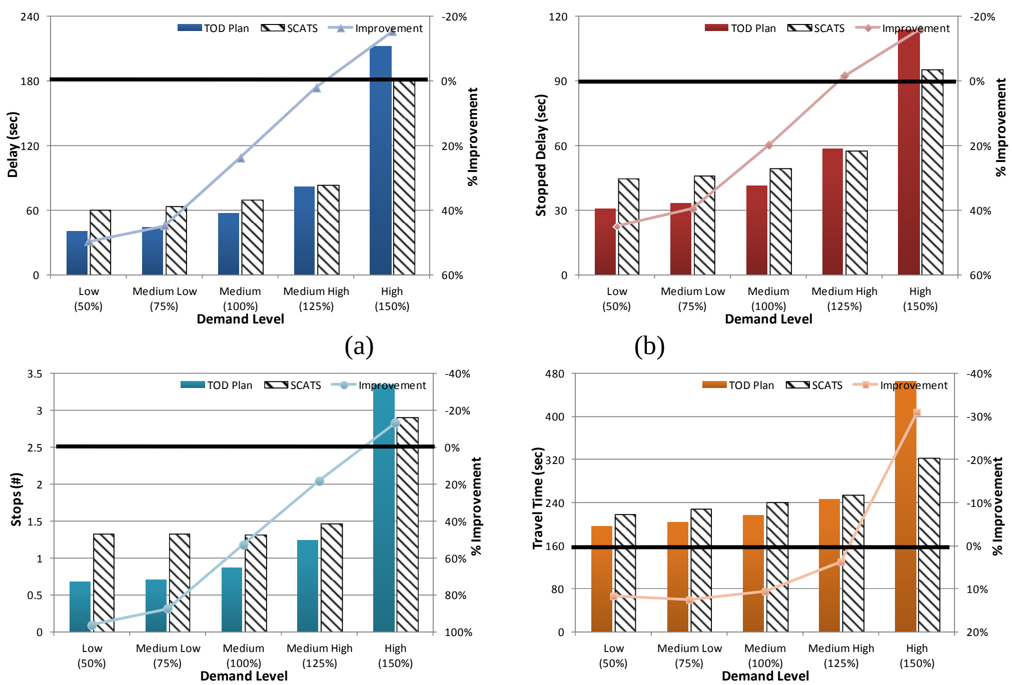


(a) (b)



(c) (d)

Figure 2.3-6 SCATS Performance for Node Level MOEs



(a) (b)

(c) (d)

Figure 2.3-7 SCATS Performance for Route Level MOEs

The Node Level and Route Level MOEs showed similar trends as the Network Level MOEs. However, the improvement was not as significant as the Network Level MOEs.

Detailed MOEs and Analyses

- **Summary of Network Level MOEs**

Summary of the Network Level MOEs is given in Table 2.3-25. Unlike the other cases analyzed so far, "Stopped Delay" at all demand levels showed reduction with SCATS.

Table 2.3-25 Network Level MOEs (Directional Flow-1)

	MOEs	TOD Plan	SCATS	% Change
Low	Delay	66.2	69.5	5.1%
	Stopped Delay	52.9	51.8	-2.2%
	Stops	1.2	1.6	39.0%
	Speed	26.8	26.4	-1.4%

Medium Low	Delay	71.0	75.4	6.2%
	Stopped Delay	55.6	55.1	-0.9%
	Stops	1.2	1.6	35.6%
	Speed	26.1	25.6	-2.1%
Medium	Delay	82.3	83.2	1.1%
	Stopped Delay	62.9	60.0	-4.6%
	Stops	1.4	1.7	22.4%
	Speed	24.8	24.6	-0.6%
Medium High	Delay	113.4	95.1	-16.1%
	Stopped Delay	81.8	67.3	-17.7%
	Stops	1.8	1.8	-0.3%
	Speed	21.8	23.5	7.7%
High	Delay	285.6	188.4	-34.0%
	Stopped Delay	147.1	102.9	-30.1%
	Stops	4.6	3.1	-33.5%
	Speed	13.1	17.0	29.5%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

- **Statistical Analysis for Node Level MOEs**

Table 2.3-26 summarizes the Node Level MOEs and comparison results, and detailed statistical t-test results are shown from Table 2.3-27 to Table 2.3-30.

Table 2.3-26 Node Level MOEs (Directional Flow-1)

	MOEs	TOD Plan	SCATS	% Change
Low	Delay	21.6	22.4	3.9%
	Stopped Delay	17.2	16.8	-2.8%
	Stops	0.39	0.52	32.1%
	Queue	13.4	12.5	-6.9%
Medium Low	Delay	23.3	24.7	6.1%
	Stopped Delay	18.3	18.2	-0.7%
	Stops	0.41	0.54	31.2%
	Queue	20.5	19.7	-3.9%
Medium	Delay	27.2	27.3	0.2%
	Stopped Delay	20.9	19.9	-4.8%
	Stops	0.46	0.55	18.0%
	Queue	30.4	30.2	-0.8%
Medium High	Delay	35.8	31.7	-11.2%
	Stopped Delay	26.8	22.7	-15.2%
	Stops	0.59	0.60	1.3%
	Queue	58.6	43.2	-26.3%
High	Delay	62.2	48.1	-22.6%
	Stopped Delay	41.7	31.3	-25.0%
	Stops	1.01	0.82	-18.3%
	Queue	194.5	142.6	-26.7%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

Table 2.3-27 t-test Significance for Node Level Delay (Directional Flow-1)

	Low	Medium Low	Medium	Medium High	High
Node 1	S	S	S	S	S
Node 2	S	N	N	T	T
Node 3	S	S	S	N	S
Node 4	T	T	N	S	S
* Node 5	T	T	T	S	S
* Node 6	T	T	T	S	S
Node 7	S	S	T	T	T
Node 8	T	T	S	T	T
* Node 9	S	S	S	S	S
Node 10	T	T	T	T	T
Average	T	T	N	S	S

* Node with '*' are the critical intersections in the Triangle Area.

Table 2.3-28 t-test Significance for Node Level Stopped Delay (Directional Flow-1)

	Low	Medium Low	Medium	Medium High	High
Node 1	S	S	S	S	S
Node 2	S	S	S	S	N
Node 3	S	S	S	N	S
Node 4	T	T	N	S	S
* Node 5	T	T	T	S	S
* Node 6	T	T	T	S	S
Node 7	S	S	N	S	S
Node 8	N	N	S	S	N
* Node 9	S	S	S	S	S
Node 10	T	T	T	T	T
Average	S	N	S	S	S

* Node with '*' are the critical intersections in the Triangle Area.

Table 2.3-29 t-test Significance for Node Level Stops (Directional Flow-1)

	Low	Medium Low	Medium	Medium High	High
Node 1	T	T	T	N	N
Node 2	T	T	T	T	T
Node 3	T	T	T	T	N
Node 4	T	T	T	T	S
* Node 5	T	T	T	N	S
* Node 6	T	T	T	S	S
Node 7	T	T	T	T	T
Node 8	T	T	T	T	T
* Node 9	S	S	S	S	S
Node 10	S	S	S	S	S
Average	T	T	T	T	S

* Node with '*' are the critical intersections in the Triangle Area.

Table 2.3-30 t-test Significance for Node Level Queue (Directional Flow-1)

	Low	Medium Low	Medium	Medium High	High
Node 1	S	S	S	S	S
Node 2	S	S	S	S	S
Node 3	S	S	N	N	T
Node 4	T	T	S	S	S
* Node 5	T	T	T	S	S
* Node 6	T	T	T	S	S
Node 7	N	N	T	T	T
Node 8	N	T	S	T	T
* Node 9	S	S	S	S	S
Node 10	T	T	T	T	T
Average	S	N	N	S	S

* Node with '*' are the critical intersections in the Triangle Area.

The Node Level MOEs generally showed improved performance by SCATS, indicating SCATS system's strong ability in handling directional traffic flow variations. While SCATS achieved better MOEs in most cases, it still showed increase in Stops.

- **Statistical Analysis for Route Level MOEs**

The Route Level MOEs and comparison results are summarized in Table 2.3-31, and Table 2.3-32 to Table 2.3-35 include detailed statistical t-test results.

Table 2.3-31 Route Level MOEs (Directional Flow-1)

	MOEs	TOD Plan	SCATS	% Change
Low	Delay	40.2	60.2	49.6%
	Stopped Delay	30.8	44.7	45.0%
	Stops	0.68	1.33	96.1%
	Travel Time	196.3	219.3	11.7%
Medium Low	Delay	44.0	63.8	44.8%
	Stopped Delay	33.1	46.2	39.6%
	Stops	0.71	1.33	87.4%
	Travel Time	202.4	227.9	12.6%
Medium	Delay	56.6	70.0	23.8%
	Stopped Delay	41.4	49.7	19.9%
	Stops	0.86	1.32	52.6%
	Travel Time	217.2	240.4	10.7%
Medium High	Delay	81.6	83.3	2.1%
	Stopped Delay	58.6	57.7	-1.5%
	Stops	1.25	1.47	18.1%
	Travel Time	245.3	254.7	3.8%
High	Delay	212.4	180.0	-15.2%
	Stopped Delay	113.6	95.5	-15.9%
	Stops	3.34	2.90	-13.1%
	Travel Time	466.0	322.4	-30.8%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

Table 2.3-32 t-test Significance for Route Level Delay (Directional Flow-1)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	T	S	S
Route 2	T	T	T	T	T
Route 3	S	S	S	N	T
Route 4	N	S	S	N	N
Route 5	S	S	N	T	T
Route 6	T	T	T	N	S
Route 7	S	S	T	N	S
Route 8	T	T	T	T	S
Route 9	S	S	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	N	T
Route 13	N	S	T	T	T
Route 14	N	S	N	T	T
Route 15	T	T	T	S	S
* Route 16	T	T	T	T	T
** Route 17	T	T	T	S	S
Average	T	T	T	N	S

* Route with * represents through route.

** Route 17 is the Peak direction through route.

Table 2.3-33 t-test Significance for Route Level Stopped Delay (Directional Flow-1)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	N	S	S
Route 2	T	T	T	T	N
Route 3	S	S	S	N	T
Route 4	S	S	S	N	N
Route 5	S	S	S	N	N
Route 6	T	N	T	T	S
Route 7	S	N	T	N	S
Route 8	T	T	T	N	S
Route 9	S	S	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	T	T
Route 13	N	S	T	T	T
Route 14	S	S	N	T	T
Route 15	T	T	T	S	S
* Route 16	T	T	T	T	T
** Route 17	T	T	T	S	S
Average	T	T	T	N	S

* Route with * represents through route.

** Route 17 is the Peak direction through route.

Table 2.3-34 t-test Significance for Route Level Stops (Directional Flow-1)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	T	N	S
Route 2	T	T	T	T	T
Route 3	S	S	N	N	T
Route 4	T	N	N	T	T
Route 5	T	T	T	T	T
Route 6	T	T	T	N	S
Route 7	S	S	S	S	S
Route 8	N	T	T	T	N
Route 9	S	N	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	T	T
Route 13	T	T	T	T	T
Route 14	T	T	T	T	T
Route 15	T	T	T	N	S
* Route 16	T	T	T	T	T
** Route 17	T	T	T	N	S
Average	T	T	T	T	S

* Route with * represents through route.

** Route 17 is the Peak direction through route.

Table 2.3-35 t-test Significance for Route Travel Time (Directional Flow-1)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	T	S	S
Route 2	T	T	T	T	T
Route 3	S	S	S	S	T
Route 4	N	S	S	N	T
Route 5	S	S	N	T	N
Route 6	T	N	T	N	S
Route 7	S	S	T	N	T
Route 8	T	T	T	T	S
Route 9	S	S	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	T	T
Route 13	T	S	T	T	T
Route 14	S	S	S	N	N
Route 15	T	T	T	S	S
* Route 16	T	T	T	T	T
** Route 17	T	T	T	S	S
Average	T	T	T	T	S

* Route with * represents through route.

** Route 17 is the Peak direction through route.

The Route Level MOEs generally showed worse performance by SCATS, except for the High demand level where SCATS showed better performance. This similar trend was also found for the arterial through routes.

In general, based on the Network and Node level MOEs, SCATS showed better performance in reducing Stopped Delay and Queue under the case of Directional Flow-1. SCATS also showed improvements for Route Level MOEs at High demand levels.

2.3.5 Case 005 – Directional Flow-2

Overall Performance

Case 005 was another directional flow case, but with the northbound being the peak direction. Figure 2.3-8 to Figure 2.3-10 illustrate the comparison results between TOD and SCATS system under three demand levels.

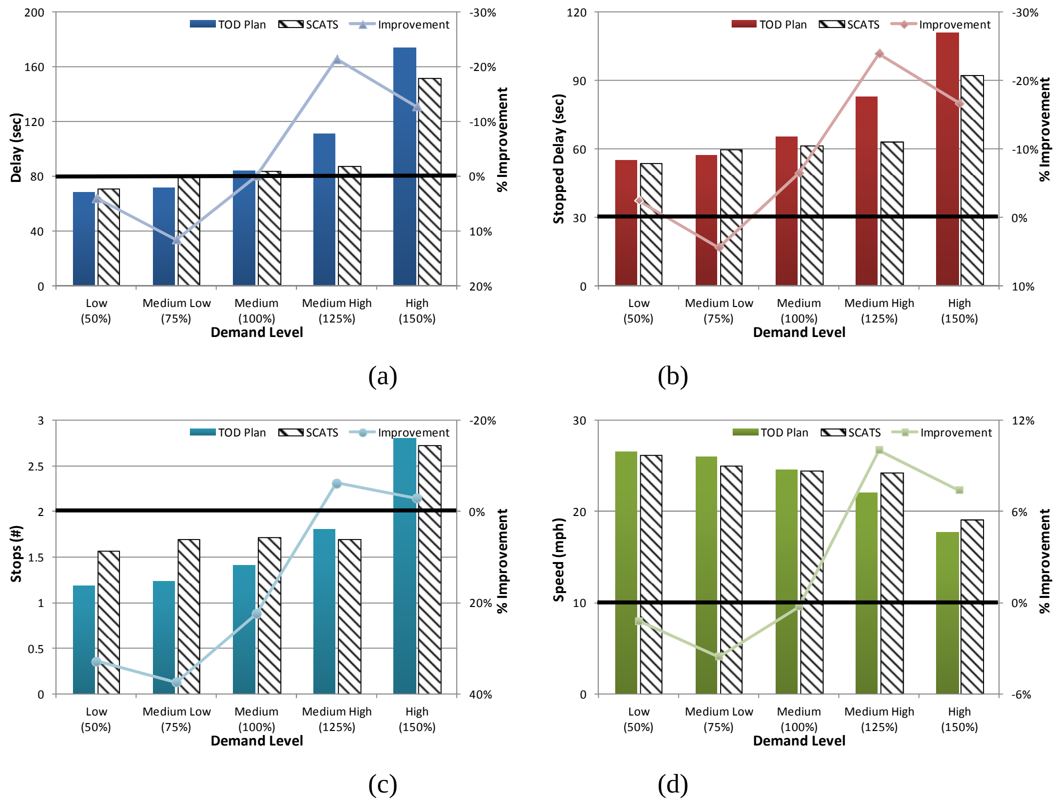


Figure 2.3-8 SCATS Performance for Network Level MOEs

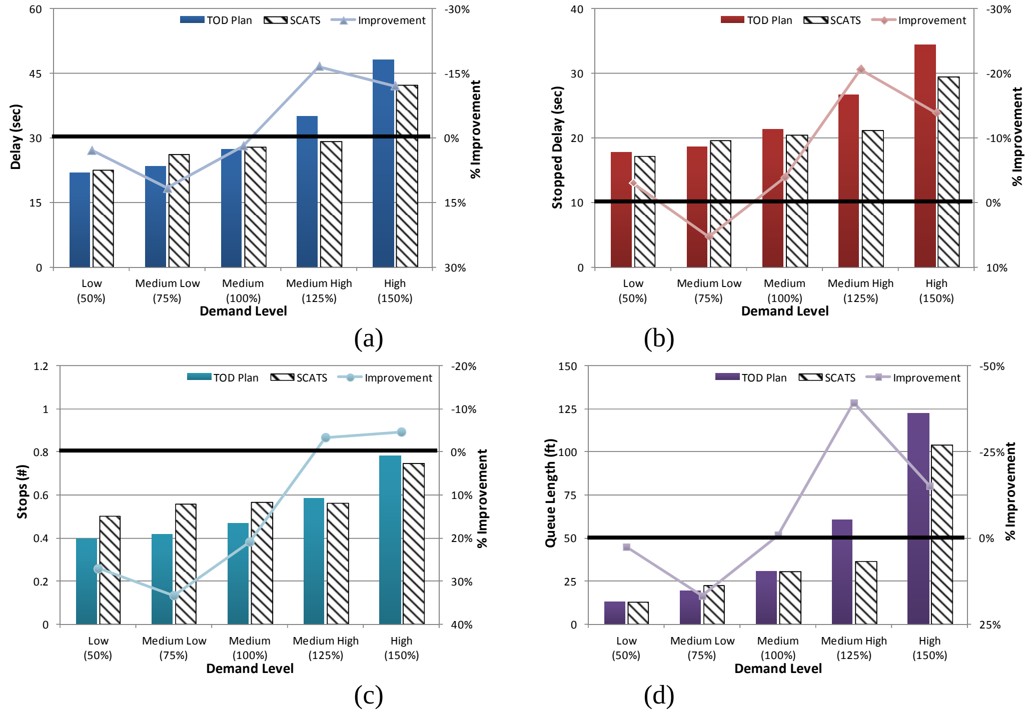


Figure 2.3-9 SCATS Performance for Node Level MOEs

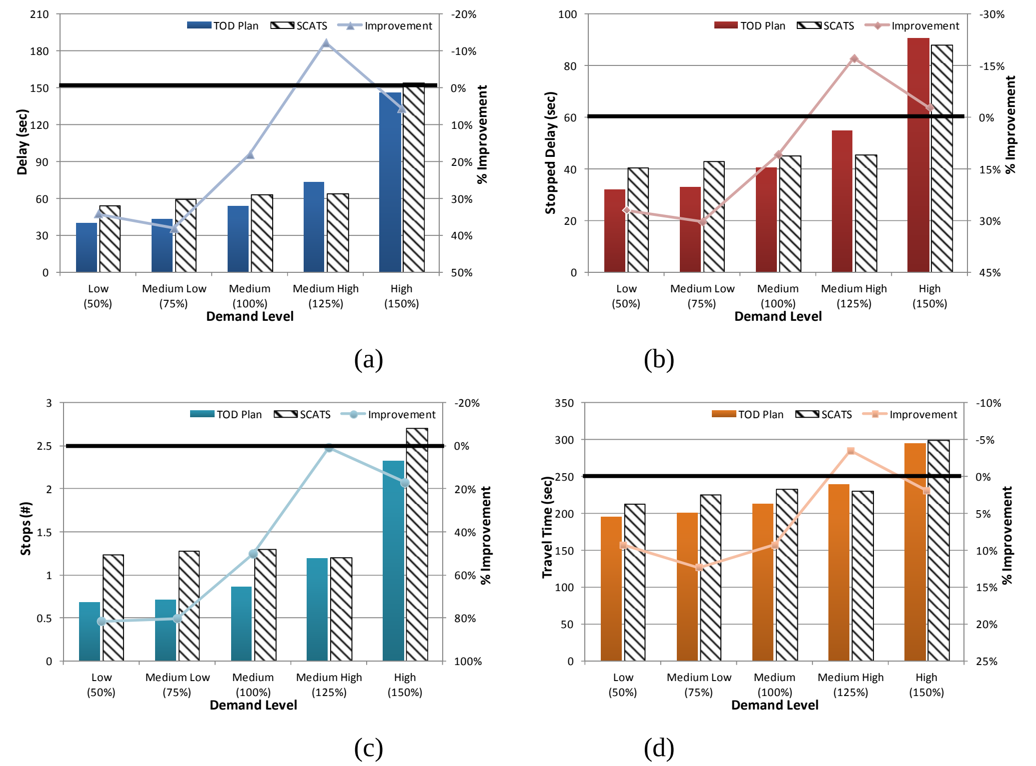


Figure 2.3-10 SCATS Performance for Route Level MOEs

In general, it showed a similar trend as Case 004. While SCATS showed slightly better performance at the high demand level, the difference is not so significant. At the Route Level, SCATS produced more Stops at all demand levels.

Detailed MOEs and Analyses

- **Summary of Network Level MOEs**

The Network Level MOEs and comparison results are repeated again in Table 2.3-36. Similar to the other cases discussed earlier, all four MOEs were improved by SCATS system at the Medium High and High demand levels.

Table 2.3-36 Network Level MOEs (Directional Flow-2)

	MOEs	TOD Plan	SCATS	% Change
Low	Delay	68.1	70.8	4.0%
	Stopped Delay	55.0	53.7	-2.5%
	Stops	1.2	1.6	32.8%
	Speed	26.5	26.2	-1.2%
Medium Low	Delay	72.1	80.4	11.6%
	Stopped Delay	57.2	59.7	4.4%
	Stops	1.2	1.7	37.4%
	Speed	26.0	25.0	-3.6%
Medium	Delay	84.2	84.2	0.0%
	Stopped Delay	65.5	61.3	-6.4%
	Stops	1.4	1.7	22.4%
	Speed	24.6	24.5	-0.3%
Medium High	Delay	110.9	87.2	-21.4%
	Stopped Delay	82.7	63.0	-23.9%
	Stops	1.8	1.7	-6.2%
	Speed	22.1	24.3	10.0%
High	Delay	174.0	151.8	-12.8%
	Stopped Delay	110.8	92.3	-16.7%
	Stops	2.8	2.7	-2.9%
	Speed	17.8	19.1	7.4%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

- **Statistical Analysis for Node Level MOEs**

Table 2.3-37 summarizes the Node Level MOEs and comparison, and Table 2.3-38 to Table 2.3-41 include detailed statistical t-test results.

The Node Level MOEs were similar to the Network Level's results. SCATS showed improvement on Stopped Delay in four out of five demand levels. All four MOEs were improved by SCATS at the Medium High and High demand levels.

Table 2.3-37 Node Level MOEs (Directional Flow-2)

	MOEs	TOD Plan	SCATS	% Change
Low	Delay	22.0	22.6	2.8%
	Stopped Delay	17.7	17.2	-3.0%
	Stops	0.40	0.50	27.0%
	Queue	12.9	13.2	2.6%
Medium Low	Delay	23.5	26.3	11.7%
	Stopped Delay	18.6	19.6	5.3%
	Stops	0.42	0.56	33.4%
	Queue	19.7	23.0	16.7%
Medium	Delay	27.4	27.9	1.9%
	Stopped Delay	21.3	20.5	-3.9%
	Stops	0.47	0.57	20.9%
	Queue	30.9	30.7	-0.8%
Medium High	Delay	35.0	29.2	-16.5%
	Stopped Delay	26.7	21.2	-20.6%
	Stops	0.58	0.56	-3.3%
	Queue	60.8	36.9	-39.2%
High	Delay	48.0	42.2	-12.0%
	Stopped Delay	34.3	29.5	-13.9%
	Stops	0.78	0.75	-4.6%
	Queue	122.6	104.0	-15.1%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

Table 2.3-38 t-test Significance for Node Level Stopped Delay (Directional Flow-2)

	Low	Medium Low	Medium	Medium High	High
Node 1	S	S	S	S	N
Node 2	S	N	T	S	T
Node 3	S	S	S	S	T
Node 4	T	T	T	N	S
* Node 5	T	T	T	S	S
* Node 6	T	T	T	S	S
Node 7	S	S	S	S	S
Node 8	S	N	S	S	N
* Node 9	S	S	S	S	S
Node 10	T	T	T	T	T
Average	T	T	N	S	S

* Node with '*' are the critical intersections in the Triangle Area.

Table 2.3-39 t-test Significance for Node Level Delay (Directional Flow-2)

	Low	Medium Low	Medium	Medium High	High
Node 1	S	S	S	S	N
Node 2	S	N	N	S	N
Node 3	S	S	S	S	N
Node 4	T	T	T	N	S
* Node 5	T	T	T	S	S
* Node 6	T	T	T	S	S
Node 7	S	S	S	S	S
Node 8	S	S	S	S	S
* Node 9	S	S	S	S	S
Node 10	T	T	T	T	T
Average	S	T	S	S	S

* Node with '*' are the critical intersections in the Triangle Area.

Table 2.3-40 t-test Significance for Node Level Stops (Directional Flow-2)

	Low	Medium Low	Medium	Medium High	High
Node 1	T	T	T	T	T
Node 2	T	T	T	T	T
Node 3	T	T	T	T	T
Node 4	T	T	T	T	S
* Node 5	T	T	T	T	N
* Node 6	T	T	T	S	S
Node 7	T	T	N	N	N
Node 8	T	T	T	N	T
* Node 9	S	S	S	S	S
Node 10	S	S	S	S	S
Average	T	T	T	S	S

* Node with '*' are the critical intersections in the Triangle Area.

Table 2.3-41 t-test Significance for Node Level Queue (Directional Flow-2)

	Low	Medium Low	Medium	Medium High	High
Node 1	N	N	N	S	N
Node 2	N	N	N	S	N
Node 3	S	S	S	S	T
Node 4	T	T	S	S	S
* Node 5	T	T	T	T	N
* Node 6	T	T	N	S	S
Node 7	S	S	S	S	N
Node 8	S	N	S	N	N
* Node 9	S	S	S	S	S
Node 10	T	T	T	T	T
Average	N	T	N	S	S

* Node with '*' are the critical intersections in the Triangle Area.

- **Statistical Analysis for Route Level MOEs**

The Route Level MOEs are summarized in Table 2.3-42, and the statistical t-test results are shown in Table 2.3-43 to Table 2.3-46.

Table 2.3-42 Route Level MOEs (Directional Flow-2)

	MOEs	TOD Plan	SCATS	% Change
Low	Delay	40.4	54.2	34.2%
	Stopped Delay	31.8	40.4	27.0%
	Stops	0.68	1.23	81.5%
	Travel Time	195.2	213.3	9.3%
Medium Low	Delay	42.9	59.2	38.1%
	Stopped Delay	33.0	43.0	30.4%
	Stops	0.71	1.28	80.3%
	Travel Time	200.3	225.1	12.4%
Medium	Delay	53.7	63.4	18.1%
	Stopped Delay	40.6	45.1	10.9%
	Stops	0.86	1.30	50.3%
	Travel Time	213.3	233.1	9.3%
Medium High	Delay	73.3	64.4	-12.2%
	Stopped Delay	54.9	45.5	-17.1%
	Stops	1.19	1.20	0.8%
	Travel Time	238.9	230.6	-3.5%
High	Delay	146.1	154.2	5.5%
	Stopped Delay	90.4	87.9	-2.8%
	Stops	2.32	2.71	16.9%
	Travel Time	294.1	299.8	1.9%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

Table 2.3-43 t-test Significance for Route Level Delay (Directional Flow-2)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	T	S	S
Route 2	T	T	T	N	S
Route 3	S	S	S	S	N
Route 4	S	S	S	S	N
Route 5	S	S	S	S	T
Route 6	T	T	S	S	N
Route 7	S	S	S	S	N
Route 8	T	T	T	S	N
Route 9	S	S	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	T	T
Route 13	N	N	S	N	T
Route 14	N	S	S	S	T
Route 15	T	T	T	S	N
**** Route 16**	T	T	T	T	N
*** Route 17**	T	T	T	S	S
Average	T	T	T	S	T

* Route with * represents through route.

** Route 16 is the peak direction through route.

Table 2.3-44 t-test Significance for Route Level Stopped Delay (Directional Flow-2)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	T	S	S
Route 2	T	T	N	S	N
Route 3	S	S	S	S	N
Route 4	S	S	S	S	N
Route 5	S	S	S	S	N
Route 6	T	T	S	S	T
Route 7	S	S	S	S	N
Route 8	N	T	N	S	T
Route 9	S	S	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	T	T
Route 13	N	S	S	N	T
Route 14	N	S	S	S	T
Route 15	T	T	T	S	S
** Route 16	T	T	T	T	N
* Route 17	T	T	T	S	S
Average	T	T	T	S	N

* Route with * represents through route.

** Route 16 is the peak direction through route.

Table 2.3-45 t-test Significance for Route Level Stops (Directional Flow-2)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	T	N	S
Route 2	T	T	T	T	N
Route 3	S	S	S	N	T
Route 4	N	N	N	N	N
Route 5	T	T	T	T	T
Route 6	T	T	T	S	N
Route 7	S	S	S	S	N
Route 8	S	N	N	N	N
Route 9	S	S	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	T	T
Route 13	T	T	T	T	T
Route 14	T	T	T	T	T
Route 15	T	T	T	S	N
** Route 16	T	T	T	T	T
* Route 17	T	T	T	N	N
Average	T	T	T	N	T

* Route with * represents through route.

** Route 16 is the peak direction through route.

Table 2.3-46 t-test Significance for Route Level Travel Time (Directional Flow-2)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	T	S	S
Route 2	T	T	T	N	S
Route 3	S	S	S	S	N
Route 4	N	N	S	N	N
Route 5	S	S	S	S	T
Route 6	T	T	S	S	N
Route 7	S	S	S	N	T
Route 8	T	T	T	N	N
Route 9	S	S	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	T	T
Route 13	N	N	N	T	T
Route 14	S	S	S	S	N
Route 15	T	T	T	S	N
** Route 16	T	T	T	T	N
* Route 17	T	T	T	S	S
Average	T	T	T	S	N

* Route with * represents through route.

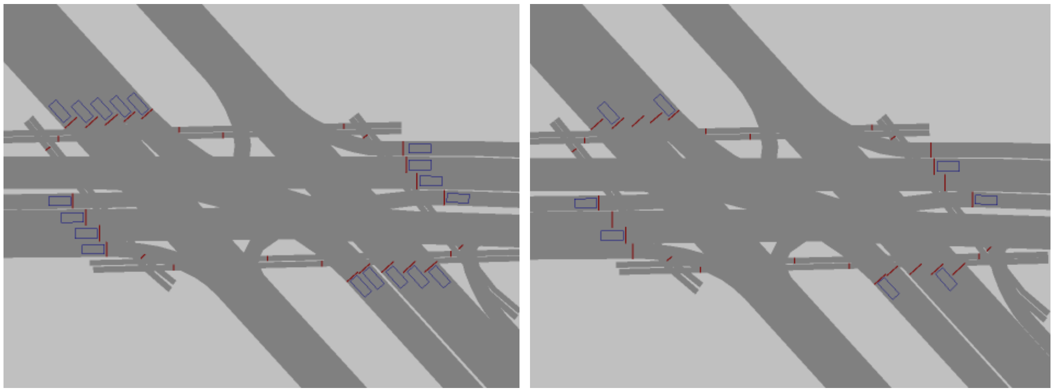
** Route 16 is the peak direction through route.

The results indicated that the improvements by SCATS for the Route Level performance were limited. SCATS showed better performance only at the Medium High demand level. At other demand levels, TOD showed either better or equivalent performance. For the arterial through route (Route 16), TOD control produced better performance at all demand levels. In this case, SCATS did not particularly favor the peak direction route.

2.3.6 Case 006 – Detector Failure-1 (NB Detector Failures)

Overall Performance

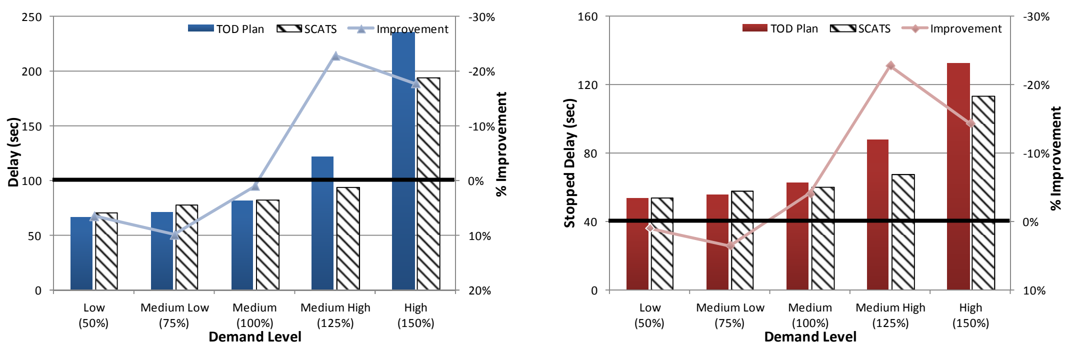
Adaptive signal control systems such as SCATS always heavily rely on detection systems. Thus, the performance of SCATS can be affected by detector failure or detector malfunction. Detector failure or detector malfunction can cause missed or false detections, resulting in inaccurate traffic flow information which is key inputs to the control algorithms. Case 006 to Case 009 were designed to assess the degree of impact on system performance due to different detector failures. The detector failure was simulated by deleting some of the detectors in the simulation network. An example of simulating detector failure is shown in Figure 2.3-11.



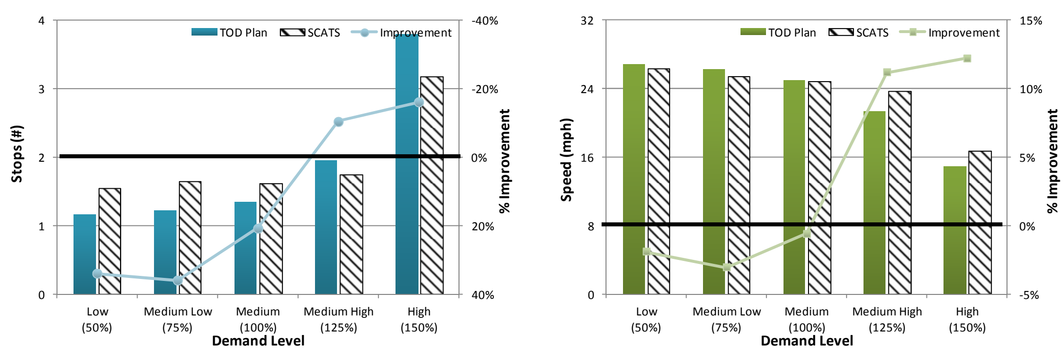
(a) Base Case (b) Some Detectors are Deleted

Figure 2.3-11 Method of Simulating Detectors Failure

Case 006 represented detector failure for the northbound direction on Boulder Hwy. Only a minimum number of detectors (one for each movement or approach) were kept in the NB direction to maintain normal operations for both SCATS and TOD coordination. Figure 2.3-12 to Figure 2.3-14 illustrate the comparison results between TOD plan and SCATS system.



(a) (b)



(c) (d)

Figure 2.3-12 SCATS Performance for Network Level MOEs – One Direction Detector Failures

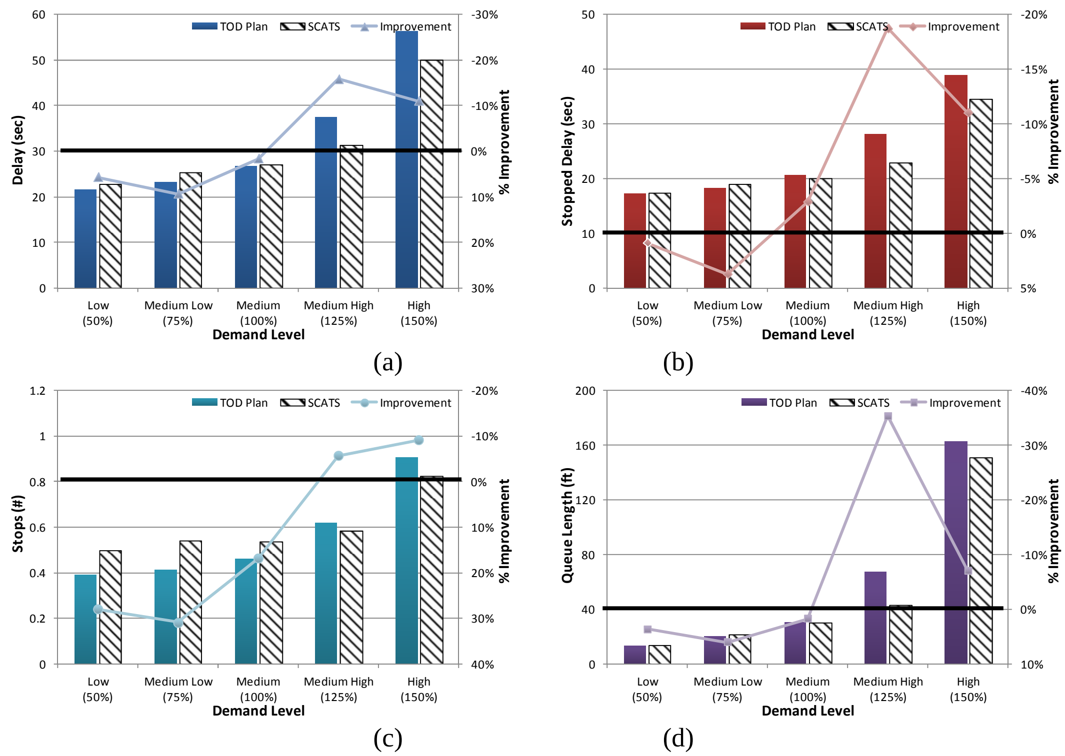


Figure 2.3-13 SCATS Performance for Node Level MOEs – One Direction Detector Failures

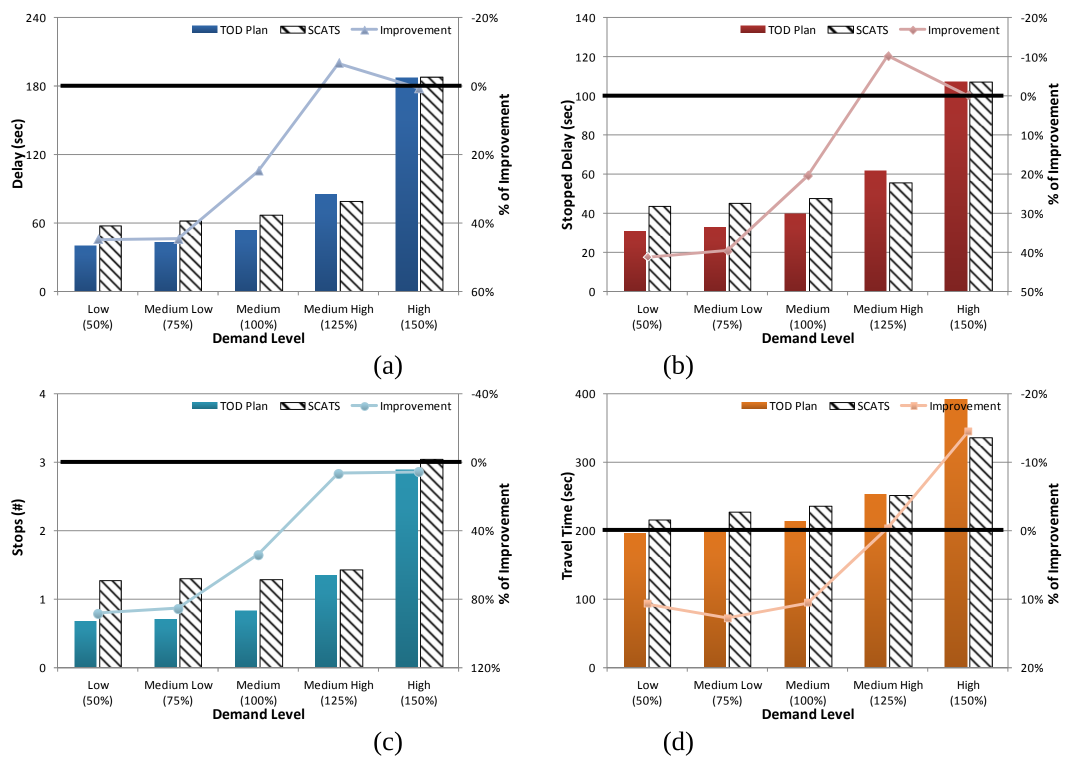


Figure 2.3-14 SCATS Performance for Route Level MOEs – One Direction Detector Failures

The results in the figures revealed similar trends as normal operations. There was no indication that detector failure significantly affected either SCATS or TOD. As before, SCATS showed better performance at the Medium High and High demand levels for the Network Level and Node Level MOEs. At the Route Level, SCATS produced more Stops at all demand levels. The less impact of detector failure may be due to the fact that a minimum number of detectors had kept for maintaining normal operations for both control systems. A total detector failure was not simulated because the simulation model could not recognize such failures as in the field operations when signals would be simply put in flash or free mode.

Detailed MOEs and Analyses

- **Summary of Network Level MOEs**

A summary of Network Level MOEs is again presented in Table 2.3-47. At the Network Level, SCATS showed better performance at the Medium High and High demand levels.

Table 2.3-47 Network Level MOEs (Detector Failure-1)

	MOEs	TOD Plan	SCATS	% Change
Low	Delay	66.5	70.8	6.5%
	Stopped Delay	53.3	53.8	1.0%
	Stops	1.2	1.6	33.9%
	Speed	26.8	26.3	-1.9%
Medium Low	Delay	70.9	77.9	9.8%
	Stopped Delay	55.8	57.8	3.6%
	Stops	1.2	1.7	35.9%
	Speed	26.2	25.4	-3.1%
Medium	Delay	81.2	82.1	1.1%
	Stopped Delay	62.6	60.0	-4.1%
	Stops	1.3	1.6	20.6%
	Speed	25.0	24.8	-0.6%
Medium High	Delay	121.5	93.8	-22.8%
	Stopped Delay	87.8	67.8	-22.7%
	Stops	2.0	1.8	-10.4%
	Speed	21.3	23.7	11.2%
High	Delay	235.7	193.9	-17.7%
	Stopped Delay	132.5	113.6	-14.3%
	Stops	3.8	3.2	-16.0%
	Speed	14.9	16.8	12.2%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

- **Statistical Analysis for Node Level MOEs**

A summary of the Node Level MOEs and comparison result is shown in Table 2.3-48, and Table 2.3-49 to Table 2.3-52 include detailed t-test results.

Table 2.3-48 Node Level MOEs (Detector Failure-1)

	MOEs	TOD Plan	SCATS	% Change
Low	Delay	21.5	22.7	5.7%
	Stopped Delay	17.2	17.4	0.9%
	Stops	0.39	0.50	28.0%
	Queue	13.2	13.7	3.6%
Medium Low	Delay	23.2	25.4	9.4%
	Stopped Delay	18.3	18.9	3.7%
	Stops	0.41	0.54	30.8%
	Queue	20.3	21.6	6.0%
Medium	Delay	26.7	27.1	1.6%
	Stopped Delay	20.6	20.0	-2.9%
	Stops	0.46	0.54	16.8%
	Queue	30.1	30.6	1.7%
Medium High	Delay	37.4	31.5	-15.8%
	Stopped Delay	28.2	22.9	-18.7%
	Stops	0.62	0.58	-5.7%
	Queue	67.3	43.5	-35.3%
High	Delay	56.2	50.1	-10.9%
	Stopped Delay	38.8	34.5	-11.0%
	Stops	0.91	0.82	-9.2%
	Queue	162.4	151.1	-7.0%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

Table 2.3-49 t-test Significance for Node Level Delay (Detector Failure-1)

Delay	Low	Medium Low	Medium	Medium High	High
Node 1	S	S	S	S	S
Node 2	T	T	T	T	T
Node 3	S	S	S	T	T
Node 4	T	T	T	S	S
*** Node 5**	T	T	T	S	S
*** Node 6**	T	T	T	S	S
Node 7	S	S	N	S	N
Node 8	N	N	S	S	T
*** Node 9**	S	S	S	S	S
Node 10	T	T	T	T	T
Average	T	T	T	S	S

* Node with '*' are the critical intersections in the Triangle Area.

Table 2.3-50 t-test Significance for Node Level Stopped Delay (Detector Failure-1)

Stopped Delay	Low	Medium Low	Medium	Medium High	High
Node 1	S	S	S	S	S
Node 2	N	T	T	T	T
Node 3	S	S	S	T	T
Node 4	T	T	T	S	S
* Node 5	T	T	T	S	S
* Node 6	T	T	T	S	S
Node 7	S	S	S	S	S
Node 8	S	S	S	S	T
* Node 9	S	S	S	S	S
Node 10	T	T	T	T	T
Average	N	T	S	S	S

* Node with '*' are the critical intersections in the Triangle Area.

Table 2.3-51 t-test Significance for Node Level Stops (Detector Failure-1)

Stops	Low	Medium Low	Medium	Medium High	High
Node 1	S	N	N	T	S
Node 2	T	T	T	T	T
Node 3	T	T	T	T	T
Node 4	T	T	T	T	S
* Node 5	T	T	T	S	S
* Node 6	T	T	T	S	S
Node 7	T	T	T	T	T
Node 8	T	T	N	T	T
* Node 9	S	S	S	S	N
Node 10	S	S	S	S	S
Average	T	T	T	S	S

* Node with '*' are the critical intersections in the Triangle Area.

Table 2.3-52 t-test Significance for Node Level Queue (Detector Failure-1)

Queue	Low	Medium Low	Medium	Medium High	High
Node 1	S	N	S	N	S
Node 2	T	T	T	T	T
Node 3	S	S	S	T	T
Node 4	T	T	S	S	S
* Node 5	T	T	T	S	S
* Node 6	T	T	T	S	S
Node 7	N	N	T	T	T
Node 8	S	N	S	S	T
* Node 9	S	S	S	S	S
Node 10	T	T	T	T	T
Average	T	T	N	S	S

* Node with '*' are the critical intersections in the Triangle Area.

The simulation results for the Node Level MOEs were similar to the Network Level's results, as all four MOEs in Medium High and High demand level were improved by SCATS.

- **Statistical Analysis for Route Level MOEs**

The Route Level MOEs and the statistical analyses results are presented in Table 2.3-53 to Table 2.3-57.

Table 2.3-53 Route Level MOEs (Detector Failure-1)

	MOEs	TOD Plan	SCATS	% Change
Low	Delay	40.2	57.6	43.5%
	Stopped Delay	30.9	43.1	39.5%
	Stops	0.68	1.27	86.4%
	Travel Time	195.8	216.1	10.4%
Medium Low	Delay	43.7	63.5	45.4%
	Stopped Delay	33.0	46.1	39.6%
	Stops	0.71	1.34	87.4%
	Travel Time	202.5	227.7	12.4%
Medium	Delay	54.2	67.0	23.7%
	Stopped Delay	40.1	47.6	18.9%
	Stops	0.85	1.31	53.7%
	Travel Time	215.2	236.5	9.9%
Medium High	Delay	79.9	79.0	-1.2%
	Stopped Delay	58.4	54.9	-6.1%
	Stops	1.24	1.43	15.2%
	Travel Time	245.2	250.2	2.1%
High	Delay	180.4	176.9	-1.9%
	Stopped Delay	106.1	98.8	-6.9%
	Stops	2.76	2.88	4.5%
	Travel Time	364.6	324.3	-11.1%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

Table 2.3-54 t-test Significance for Route Level Delay (Detector Failure-1)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	T	S	S
Route 2	T	T	T	T	T
Route 3	S	S	S	N	T
Route 4	S	S	S	N	T
Route 5	S	S	S	T	T
Route 6	T	T	T	N	S
Route 7	S	S	N	S	N
Route 8	N	T	T	N	N
Route 9	S	S	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	T	T
Route 13	N	S	N	T	T
Route 14	N	S	N	T	T
Route 15	T	T	T	S	S
** Route 16	T	T	T	T	T
* Route 17	T	T	T	S	S
Average	T	T	T	S	N

* Route with * represents through route.

** Route 16 is the critical route for this case.

Table 2.3-55 t-test Significance for Route Level Stopped Delay (Detector Failure-1)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	T	S	S
Route 2	T	T	T	N	T
Route 3	S	S	S	N	T
Route 4	S	S	S	N	T
Route 5	S	S	S	N	N
Route 6	T	T	T	T	S
Route 7	S	S	N	S	N
Route 8	N	T	N	N	N
Route 9	S	S	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	T	T
Route 13	N	S	S	T	T
Route 14	S	S	N	T	T
Route 15	T	T	T	S	S
** Route 16	T	T	T	T	T
* Route 17	T	T	T	S	S
Average	T	T	T	S	N

* Route with * represents through route.

** Route 16 is the critical route for this case.

Table 2.3-56 t-test Significance for Route Level Stops (Detector Failure-1)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	T	S	S
Route 2	T	T	T	T	T
Route 3	S	S	N	N	T
Route 4	N	N	S	N	T
Route 5	T	T	T	T	T
Route 6	T	T	T	N	S
Route 7	S	S	S	S	N
Route 8	S	T	N	N	N
Route 9	S	S	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	T	T
Route 13	T	T	T	T	T
Route 14	T	T	T	T	T
Route 15	T	T	T	S	S
** Route 16	T	T	T	T	T
* Route 17	T	T	T	N	S
Average	T	T	T	T	N

* Route with * represents through route.

** Route 16 is the critical route for this case.

Table 2.3-57 t-test Significance for Route Level Travel Time (Detector Failure-1)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	T	S	S
Route 2	T	T	T	T	T
Route 3	S	S	S	S	T
Route 4	S	S	N	T	T
Route 5	S	S	N	T	T
Route 6	T	T	N	N	S
Route 7	S	S	T	T	T
Route 8	T	T	T	T	N
Route 9	S	S	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	T	T
Route 13	T	N	N	T	T
Route 14	S	S	S	S	T
Route 15	T	T	T	S	S
** Route 16	T	T	T	T	T
* Route 17	T	T	T	S	S
Average	T	T	T	N	S

* Route with * represents through route.

** Route 16 is the critical route for this case.

The above comparisons reflected the overall network impact due to detector failures. In order to capture the exact impact on the affected route, the MOEs for Route 16 (the main street route where detector failures were simulated) were examined as shown in Table 2.3-58. In the table, both SCATS and TOD with detector failures were compared with the base case. The relative change in performance would reflect how detector failures affected both systems.

The following observations can be made:

- In most cases, TOD control actually showed improved performance with detector failures. A possible explanation was that detector failures on the main street had a negligible effect on the main street route because the coordinated phases would retain their allocated phase splits. It may actually favor the main street route because major street left-turn phases may get skipped or shortened.
- SCATS system generally showed worse performance with detector failures in most cases. This was expected as SCATS relies on accurate detection to achieve the expected performance.
- For both controls, detector failures resulted in negligible difference in performance under the lower demand levels. The impact on SCATS was more significant at the high demand levels.

Table 2.3-58 Comparison Result between Base Case and Case 006 for Route 16

			Low	Medium Low	Medium	Medium High	High
Delay	**TOD Plan**	Base Case	27.8	30.7	49.9	80.6	172.9
		Case 006	29.4	31.9	46.6	77.6	145.7
		% Change	5.9%	4.0%	-6.5%	-3.7%	-15.7%
	SCATS	Base Case	118.8	131.5	128.0	126.3	202.4
		Case 006	118.1	132.0	120.4	131.3	213.3
		% Change	-0.6%	0.4%	-5.9%	3.9%	5.4%
Stopped Delay	**TOD Plan**	Base Case	14.9	15.6	26.7	46.7	101.7
		Case 006	16.2	16.5	24.6	44.1	85.1
		% Change	9.3%	5.8%	-7.7%	-5.7%	-16.3%
	SCATS	Base Case	66.5	68.9	62.7	53.8	105.2
		Case 006	67.1	70.1	57.6	58.7	108.4
		% Change	0.9%	1.8%	-8.1%	9.2%	3.0%
Stops	**TOD Plan**	Base Case	0.39	0.40	0.65	1.00	2.46
		Case 006	0.41	0.43	0.58	0.93	2.01
		% Change	6.4%	7.4%	-9.9%	-6.8%	-18.2%
	SCATS	Base Case	3.63	3.75	3.32	3.11	4.01
		Case 006	3.64	3.75	3.09	3.22	4.21
		% Change	0.4%	0.1%	-6.8%	3.6%	4.9%
Travel Time	**TOD Plan**	Base Case	299.8	304.6	318.9	341.2	423.0
		Case 006	299.2	304.2	314.0	335.6	394.5
		% Change	-0.2%	-0.1%	-1.5%	-1.6%	-6.7%
	SCATS	Base Case	386.7	401.1	400.6	388.6	460.4
		Case 006	387.9	402.5	390.2	399.6	471.2
		% Change	0.3%	0.4%	-2.6%	2.8%	2.3%

* Red color indicates Base Case performed better; green color indicates current Case 006 performed better.

2.3.7 Case 007 – Detector Failure-2 (Major Street Detector Failures)

Overall Performance

Case 007 was designed to simulate detector failures on the main street in both directions. Similarly, a minimum number of detectors were kept to maintain basic operations for both control systems. Figure 2.3-15 to Figure 2.3-17 illustrate the MOEs and comparison results between TOD and SCATS system.

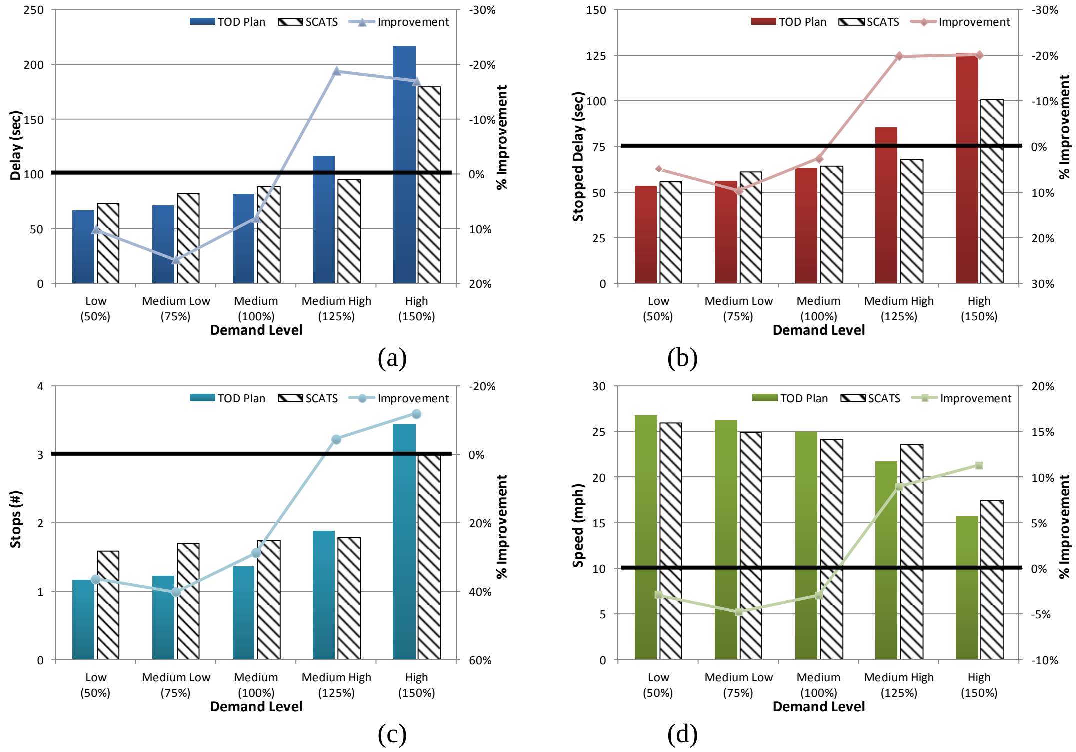


Figure 2.3-15 SCATS Performance for Network Level MOEs - Main Street Detector Failures

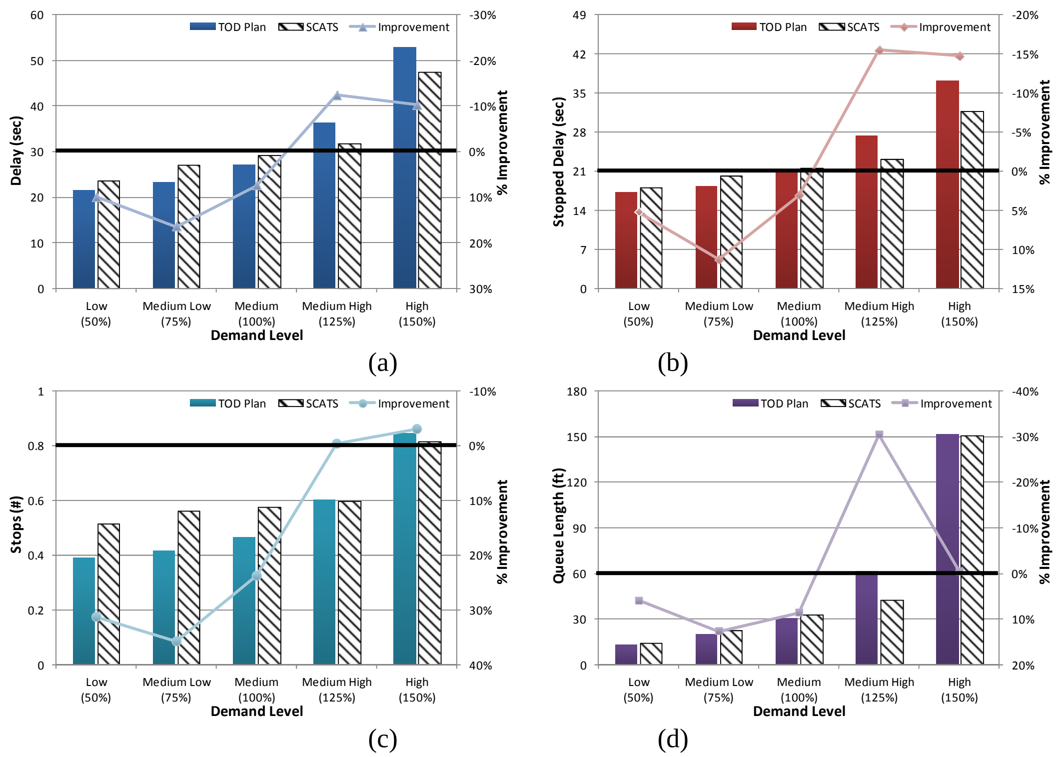
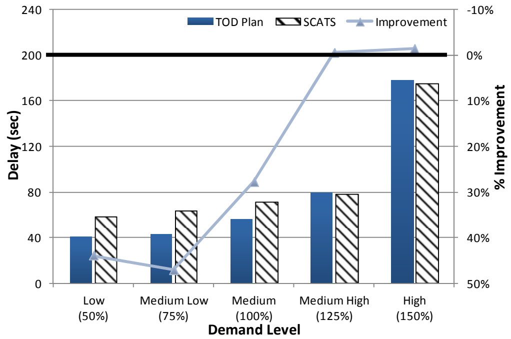
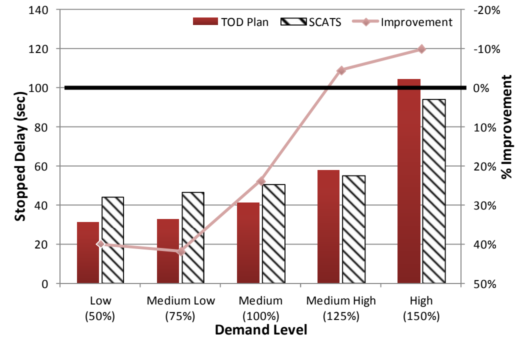


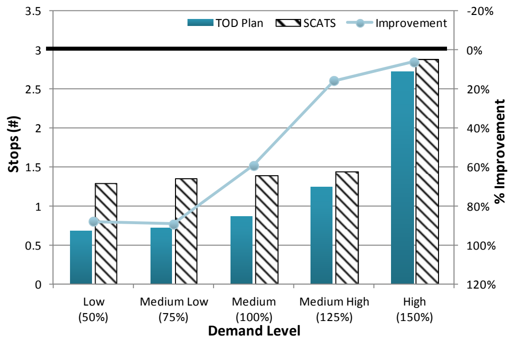
Figure 2.3-16 SCATS Performance for Node Level MOEs – Main Street Detector

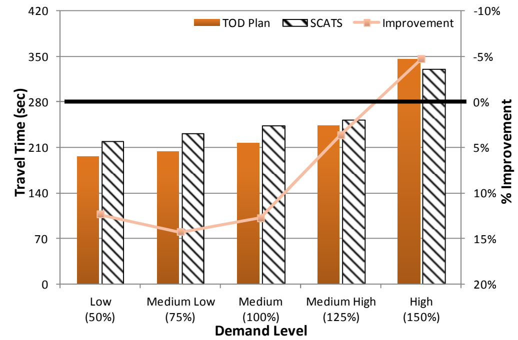
Failures





(a) (b)





(c) (d)

Figure 2.3-17 SCATS Performance for Route Level MOEs – Main Street Detector Failures

The trend was similar to Case 006. SCATS showed better performance at the Medium High and High demand levels. However, SCATS produced more Stops at all demand levels for the Route Level MOEs, and it performed slightly better at the High demand level for other three MOEs.

Detailed MOEs and Analyses

- **Summary of Network Level MOEs**

Detailed Network Level MOEs are again listed in Table 2.3-59. SCATS only showed better performance at the Medium High and High demand levels.

- **Statistical Analysis for Node Level MOEs**

The detailed Node Level MOEs and comparison results are shown in Table 2.3-60, and Table 2.3-61 to Table 2.3-64 include statistical t-test results.

Table 2.3-59 Network Level MOEs (Detector Failure-2)

	MOEs	TOD Plan	SCATS	% Change
Low	Delay	66.8	73.6	10.2%
	Stopped Delay	53.5	56.1	4.9%
	Stops	1.2	1.6	36.4%
	Speed	26.8	26.0	-2.9%
Medium Low	Delay	71.0	82.1	15.7%
	Stopped Delay	55.8	61.2	9.7%
	Stops	1.2	1.7	40.2%
	Speed	26.2	24.9	-4.8%
Medium	Delay	81.9	88.5	8.1%
	Stopped Delay	63.0	64.7	2.7%
	Stops	1.4	1.8	28.8%
	Speed	24.9	24.2	-2.9%
Medium High	Delay	116.7	94.7	-18.8%
	Stopped Delay	85.4	68.5	-19.8%
	Stops	1.9	1.8	-4.5%
	Speed	21.7	23.6	8.9%
High	Delay	216.1	179.5	-17.0%
	Stopped Delay	126.2	100.9	-20.0%
	Stops	3.4	3.0	-11.9%
	Speed	15.7	17.5	11.3%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

Table 2.3-60 Node Level MOEs (Detector Failure-2)

	MOEs	TOD Plan	SCATS	% Change
Low	Delay	21.5	23.7	9.9%
	Stopped Delay	17.2	18.1	5.2%
	Stops	0.39	0.51	31.2%
	Queue	13.4	14.2	5.9%
Medium Low	Delay	23.2	27.0	16.4%
	Stopped Delay	18.2	20.3	11.3%
	Stops	0.41	0.56	35.7%
	Queue	20.4	23.0	12.7%
Medium	Delay	27.2	29.2	7.5%
	Stopped Delay	21.0	21.6	3.1%
	Stops	0.47	0.58	23.7%
	Queue	30.4	33.0	8.6%
Medium High	Delay	36.3	31.8	-12.4%
	Stopped Delay	27.4	23.2	-15.5%
	Stops	0.60	0.60	-0.4%
	Queue	61.5	42.8	-30.4%
High	Delay	52.8	47.4	-10.2%
	Stopped Delay	37.2	31.7	-14.7%
	Stops	0.84	0.82	-3.1%
	Queue	151.6	150.8	-0.5%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

Table 2.3-61 t-test Significance for Node Level Delay (Detector Failure-2)

Delay	Low	Medium Low	Medium	Medium High	High
Node 1	S	S	S	S	S
Node 2	T	T	T	T	T
Node 3	S	S	N	N	N
Node 4	T	T	T	N	S
* Node 5	T	T	T	S	S
* Node 6	T	T	T	S	S
Node 7	N	N	T	T	T
Node 8	T	T	T	T	T
* Node 9	S	S	S	S	S
Node 10	T	T	T	T	T
Average	T	T	T	S	S

* Node with '*' are the critical intersections in the Triangle Area.

Table 2.3-62 t-test Significance for Node Level Stopped Delay (Detector Failure-2)

Stopped Delay	Low	Medium Low	Medium	Medium High	High
Node 1	S	S	S	S	S
Node 2	N	N	T	T	T
Node 3	S	S	S	N	S
Node 4	T	T	T	S	S
* Node 5	T	T	T	S	S
* Node 6	T	T	T	S	S
Node 7	N	N	T	T	N
Node 8	T	T	T	N	N
* Node 9	S	S	S	S	S
Node 10	T	T	T	T	T
Average	T	T	N	S	S

* Node with '*' are the critical intersections in the Triangle Area.

Table 2.3-63 t-test Significance for Node Level Stops (Detector Failure-2)

Stops	Low	Medium Low	Medium	Medium High	High
Node 1	S	N	T	T	N
Node 2	T	T	T	T	T
Node 3	T	T	T	T	T
Node 4	T	T	T	T	S
* Node 5	T	T	T	S	S
* Node 6	T	T	T	S	S
Node 7	T	T	T	T	T
Node 8	T	T	T	T	T
* Node 9	S	S	S	S	S
Node 10	S	S	S	S	S
Average	T	T	T	N	N

* Node with '*' are the critical intersections in the Triangle Area.

Table 2.3-64 t-test Significance for Node Level Queue (Detector Failure-2)

Queue	Low	Medium Low	Medium	Medium High	High
Node 1	N	S	N	S	S
Node 2	N	T	T	T	T
Node 3	S	S	N	T	N
Node 4	T	T	S	S	S
* Node 5	T	T	T	S	S
* Node 6	T	T	T	S	S
Node 7	T	T	T	T	T
Node 8	T	T	T	T	T
* Node 9	S	S	S	S	S
Node 10	T	T	T	T	T
Average	T	T	T	S	S

* Node with '*' are the critical intersections in the Triangle Area.

The results for Node Level MOEs were similar to the Network Level results. All four MOEs at the Medium High and High demand levels were improved by SCATS. The three intersections in the triangle area also showed similar improvements by SCATS at the Medium High and High demand levels.

- **Statistical Analysis for Route Level MOEs**

The Route Level MOEs are summarized in Table 2.3-65, and the statistical t-test results are shown in Table 2.3-66 to Table 2.3-69.

Table 2.3-65 Route Level MOEs (Detector Failure-2)

	MOEs	TOD Plan	SCATS	% Change
Low	Delay	40.7	58.6	44.0%
	Stopped Delay	31.4	44.0	40.0%
	Stops	0.69	1.29	87.9%
	Travel Time	196.0	220.2	12.4%
Medium Low	Delay	43.6	64.1	47.1%
	Stopped Delay	32.9	46.6	41.8%
	Stops	0.72	1.35	89.1%
	Travel Time	202.8	231.7	14.3%
Medium	Delay	55.7	71.1	27.7%
	Stopped Delay	41.1	51.0	23.8%
	Stops	0.87	1.39	59.1%
	Travel Time	216.5	244.1	12.8%
Medium High	Delay	79.0	78.6	-0.5%
	Stopped Delay	57.9	55.4	-4.4%
	Stops	1.25	1.44	15.8%
	Travel Time	244.1	253.0	3.6%
High	Delay	177.5	175.1	-1.3%
	Stopped Delay	104.4	94.2	-9.8%
	Stops	2.72	2.89	6.2%
	Travel Time	346.4	330.2	-4.7%

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

Table 2.3-66 t-test Significance for Route Level Delay (Detector Failure-2)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	T	S	S
Route 2	T	T	T	T	T
Route 3	S	S	S	S	N
Route 4	S	S	S	S	S
Route 5	S	S	S	T	T
Route 6	T	T	T	N	S
Route 7	S	S	T	N	S
Route 8	T	T	T	T	T
Route 9	S	S	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	T	T
Route 13	S	S	N	N	T
Route 14	S	S	N	N	T
Route 15	T	T	T	S	S
* Route 16	T	T	T	T	T
* Route 17	T	T	T	S	S
Average	T	T	T	N	N

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

Table 2.3-67 t-test Significance for Route Level Stopped Delay (Detector Failure-2)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	T	S	S
Route 2	T	T	T	T	T
Route 3	S	S	S	S	N
Route 4	S	S	S	S	S
Route 5	S	S	S	S	N
Route 6	T	T	T	T	S
Route 7	S	S	T	N	S
Route 8	T	T	T	N	T
Route 9	S	S	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	T	T
Route 13	S	S	S	N	T
Route 14	S	S	S	N	N
Route 15	T	T	T	S	S
* Route 16	T	T	T	T	T
* Route 17	T	T	T	S	S
Average	T	T	T	N	S

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

Table 2.3-68 t-test Significance for Route Level Stops (Detector Failure-2)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	T	N	S
Route 2	T	T	T	T	T
Route 3	S	S	N	N	T
Route 4	T	N	S	N	T
Route 5	T	T	T	T	T
Route 6	T	T	T	N	S
Route 7	S	S	S	S	S
Route 8	T	T	T	T	T
Route 9	S	S	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	T	T
Route 13	T	T	T	T	T
Route 14	T	T	T	T	T
Route 15	T	T	T	S	S
* Route 16	T	T	T	T	T
* Route 17	T	T	T	N	S
Average	T	T	T	T	T

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

Table 2.3-69 t-test Significance for Route Level Travel Time (Detector Failure-2)

	Low	Medium Low	Medium	Medium High	High
Route 1	T	T	T	S	S
Route 2	T	T	T	T	T
Route 3	S	S	S	S	S
Route 4	N	N	N	N	N
Route 5	S	S	S	T	T
Route 6	T	T	N	N	S
Route 7	S	S	N	T	T
Route 8	T	T	T	T	T
Route 9	S	S	S	S	S
Route 10	T	T	T	T	T
Route 11	T	T	T	T	T
Route 12	T	T	T	T	T
Route 13	N	S	N	T	T
Route 14	S	S	S	S	S
Route 15	T	T	T	S	S
* Route 16	T	T	T	T	T
* Route 17	T	T	T	N	S
Average	T	T	T	T	S

* Red color indicates TOD Plan performed better; green color indicates SCATS performed better.

In general, SCATS did not show better performance at the Route Level. SCATS only improved Stopped Delay and Travel Time at the High demand level.

Another comparison was made to just focus on the two main street routes (Routes 16 and 17) as they were mainly affected by the main street detector failures. The results are shown in Table 2.3-70 and Table 2.3-71. In the table, both SCATS and TOD with detector failures were compared with the base case. The relative change in performance would reflect how detector failures affected both systems.

Table 2.3-70 Comparison Result between Base Case and Case 007 for Route 16

			Low	Medium Low	Medium	Medium High	High
Delay	TOD Plan	Base Case	27.8	30.7	49.9	80.6	172.9
		Case 007	29.7	33.8	47.1	76.6	143.5
		% Change	6.9%	10.0%	-5.6%	-4.9%	-17.0%
	SCATS	Base Case	118.8	131.5	128.0	126.3	202.4
		Case 007	122.3	144.1	148.6	161.1	224.5
		% Change	3.0%	9.5%	16.0%	27.5%	10.9%
Stopped Delay	TOD Plan	Base Case	14.9	15.6	26.7	46.7	101.7
		Case 007	16.3	17.2	25.2	43.6	86.0
		% Change	9.7%	10.3%	-5.6%	-6.6%	-15.5%
	SCATS	Base Case	66.5	68.9	62.7	53.8	105.2
		Case 007	71.2	81.8	80.8	87.6	129.4
		% Change	7.1%	18.7%	28.9%	62.9%	23.0%
Stops	TOD Plan	Base Case	0.39	0.40	0.65	1.00	2.46
		Case 007	0.41	0.45	0.60	0.90	1.85
		% Change	5.8%	12.4%	-7.1%	-9.9%	-24.7%
	SCATS	Base Case	3.63	3.75	3.32	3.11	4.01
		Case 007	3.68	3.92	3.65	3.66	4.41
		% Change	1.4%	4.6%	9.9%	17.7%	9.9%
Travel Time	TOD Plan	Base Case	299.8	304.6	318.9	341.2	423.0
		Case 007	300.4	306.5	315.7	344.0	401.0
		% Change	0.2%	0.6%	-1.0%	0.8%	-5.2%
	SCATS	Base Case	386.7	401.1	400.6	388.6	460.4
		Case 007	390.4	410.5	418.6	425.0	487.8
		% Change	0.9%	2.3%	4.5%	9.4%	5.9%

* Red color indicates Base Case performed better; green color indicates current Case 007 performed better.

Table 2.3-71 Comparison Result between Base Case and Case 007 for Route 17

			Low	Medium Low	Medium	Medium High	High
Delay	TOD Plan	Base Case	20.9	41.4	103.1	267.6	676.2
		Case 007	21.1	41.5	114.9	264.7	629.4
		% Change	0.7%	0.4%	11.5%	-1.1%	-6.9%
	SCATS	Base Case	139.3	173.6	175.6	215.6	425.8
		Case 007	142.9	181.0	200.6	222.1	456.8
		% Change	2.6%	4.3%	14.2%	3.0%	7.3%
Stopped Delay	TOD Plan	Base Case	4.0	16.9	60.7	173.9	362.4
		Case 007	3.9	17.1	69.5	171.4	348.1
		% Change	-1.9%	1.0%	14.4%	-1.4%	-3.9%
	SCATS	Base Case	100.1	121.3	114.6	128.9	211.4
		Case 007	101.7	125.5	134.0	140.8	217.4
		% Change	1.5%	3.5%	16.9%	9.2%	2.8%
Stops	TOD Plan	Base Case	0.20	0.47	1.20	3.46	9.70
		Case 007	0.21	0.48	1.32	3.48	8.74
		% Change	7.4%	2.2%	9.8%	0.6%	-10.0%
	SCATS	Base Case	3.01	3.41	3.17	3.81	6.65
		Case 007	3.12	3.62	3.68	3.92	6.74
		% Change	3.7%	6.2%	16.1%	2.8%	1.5%
Travel Time	TOD Plan	Base Case	287.6	310.4	371.6	525.9	915.9
		Case 007	286.0	305.7	377.9	506.4	871.4
		% Change	-0.6%	-1.5%	1.7%	-3.7%	-4.9%
	SCATS	Base Case	404.9	443.5	442.6	475.7	661.0
		Case 007	408.2	442.5	469.3	479.3	696.5
		% Change	0.8%	-0.2%	6.0%	0.8%	5.4%

* Red color indicates Base Case performed better; green color indicates current Case 007 performed better.

The general observations were similar to Case 006 when detector failures occurred in one direction only. These observations were:

- Detector failures on the main street exhibited minimal impact on TOD control for the main street routes. At higher demand levels, TOD control actually showed improved performance with detector failures. As indicated before, the main street routes would retain their allocated phase splits even with some detectors failure. It may actually favor the main street routes because major street left-turn phases may get skipped or shortened.
- SCATS system generally showed worse performance with detector failures in most cases. This was expected as SCATS relies on accurate detection to achieve the expected performance.
- For both controls, detector failures resulted in negligible difference in performance under the lower demand levels. The impact on SCATS was more significant at the high demand levels.

Simulation of other detector failure scenarios was also carried, including side street detector failures and all detector failures; however, the general findings were similar to the case of partial detector failures, and the results were omitted in this report.

2.4 Summary and Findings – SCATS Evaluation

Evaluation of SCATS was conducted using a software-in-the-loop simulation platform developed in this research. A segment of Boulder Hwy in Las Vegas where SCATS was implemented in the field was modeled. As SCATS has a memory feature to cause starting a controlled environment based on past events and performance, a single long run with multiple peaks was adopted in this study.

The evaluation was primarily based on side-to-side comparison between optimized TOD plan and SCATS. A total of 27 scenarios which were classified into seven different cases under five demand levels were analyzed. For each scenario, simulation results were compared at three different levels to provide more comprehensive evaluation results, in which delay, stopped delay, stops, speed, queue, and travel time were selected to measure the effectiveness of SCATS. The major findings are summarized as follows:

- Based on the Network Level MOEs, SCATS consistently showed better performance at the higher level traffic demands. In our analyses, such higher traffic demand levels resembled demand exceeding capacity at the key intersections in the system.
- Detailed examination of Network Level performance revealed that SCATS achieved better results in minimizing delays than stops. However, the higher number of stops was an indication of less optimal progression, which may suggest room for further improvement on its algorithm.
- It usually came to the same conclusion for SCATS system on Node Level evaluation. SCATS performed well at the intersection level to balance the delays and queues for all the movements. When traffic demand was at Medium High or High level, SCATS system often resulted in more significant improvements.
- For the three critical intersections in the triangle area, SCATS generally showed better performance than TOD control, especially for the scenarios with higher traffic demands.
- For the 17 routes selected for the analyses, SCATS generally did not show improvement over TOD control.
- The better performance of SCATS at the higher demand levels indicated the effectiveness of SCATS in handling shoulder effects (i.e., pre and post congestion).
- The better performance of SCATS at the Network Level than Route Level may suggest that SCATS optimized signal timing based on the entire network, where the major street and minor street were treated equally.
- The better performance of SCATS in the "New Development" case indicated SCATS can handle traffic demand growth better than TOD plan without a major re-timing effort.

- For the "Special Event" case, SCATS did not show significant improvement, which indicated SCATS may not have further ability in reacting sudden volume variations. For the "Directional Flow" cases, SCATS showed similar performance as the base case, which meant SCATS performed better at Medium High or High demand levels. Besides, SCATS was not affected much when part of the detectors failed. But when detectors on both major and minor streets failed, SCATS was affected more severely.
- Running the SCATS virtual software with a microscopic traffic simulation would still only provide limited representation of SCATS. The performance of any SCATS installation and therefore the SCATS algorithms are significantly a function of the characteristics of the underlying traffic control configuration within SCATS, implicitly the objectives of that configuration, and the expected operating traffic conditions, that are specific to that SCATS instance. The less satisfactory results under the low and medium demand levels seem to be contributed by the minimum cycle time setup in SCATS. This minimum cycle time was due to constraints of pedestrians crossing the very wide main street, which is not common at typical urban arterials. A lower minimum cycle time would perhaps be more suitable for the lower and medium demand levels simulated, but the experiment was not carried out due to time constraints.

3 ACS Lite Evaluation

Evaluation of ACS Lite was documented in this section. The network used for the evaluation was a section of Washington Avenue. The evaluation involved the microscopic traffic simulation model CORSIM running with a virtual ACS Lite software supplied by Siemens ITS. A similar approach to the SCATS evaluation was adopted.

3.1 Simulation Scheme

3.1.1 Site Description

The study network of Washington Avenue was located in the northeast part of Las Vegas, Nevada. The arterial section under study was between Main Street and Nellis Boulevard. There were a total of 11 signals. And the total length of this road section was approximately 4.4 miles. The map of the study area is shown in Figure 3.1-1.

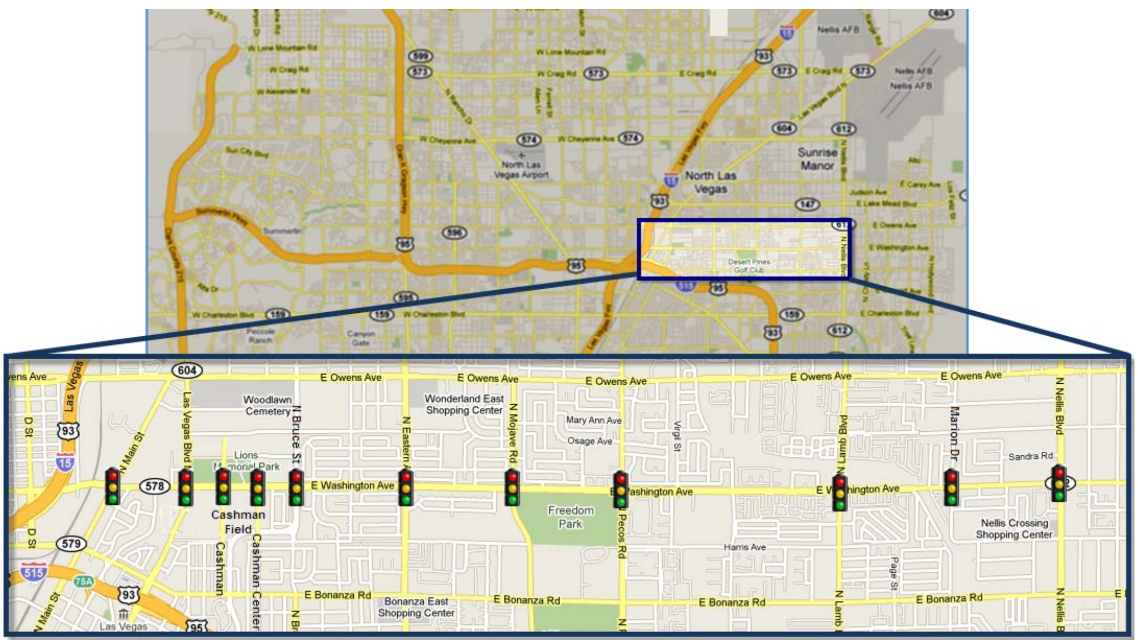
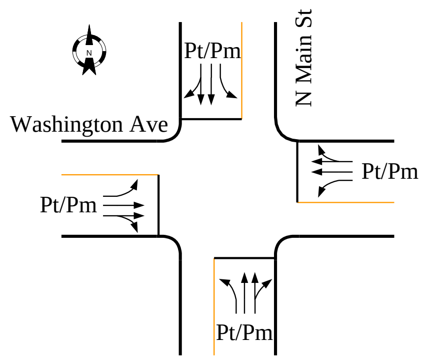


Figure 3.1-1 Map of the Study Network

Washington Avenue was relatively a minor arterial which had some unique characteristics compared with a typical urban arterial. Washington Avenue had several intersections where the cross streets were major arterials and the coordinated phases were on the cross streets. Such a situation imposed constraints to the arterial in terms of cycle length and phase splits to achieve optimal signal timing and coordination. Instead of using the existing coordinated signal timing data, a new set of coordinated actuated signal timing plans were generated using Synchro.

Detailed geometric layouts and information for the 11 intersections within the study area are shown in Table 3.1-1.

Table 3.1-1 Intersection Geometry and Signal Timing Information

<table>
<tr><th></th><th>Intersection Layout</th><th>Signal Timing Plan</th></tr>
<tr><td rowspan="2">1</td><td rowspan="2">
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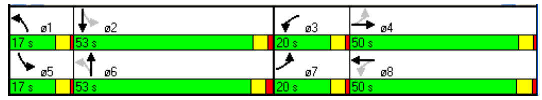

Coordinated Phase: 4, 8 (Washington Ave)</td></tr>
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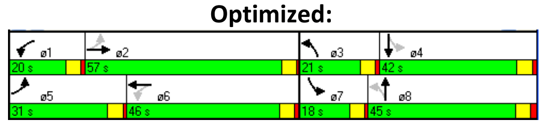

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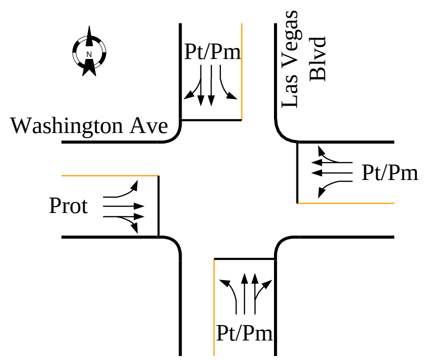
<tr><td rowspan="2">2</td><td rowspan="2">
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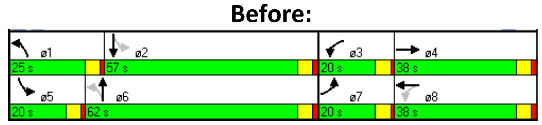

Coordinated Phase: 4, 8 (Washington Ave)</td></tr>
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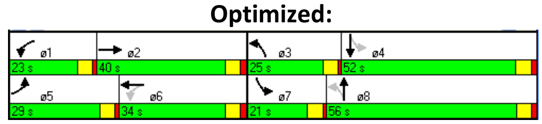

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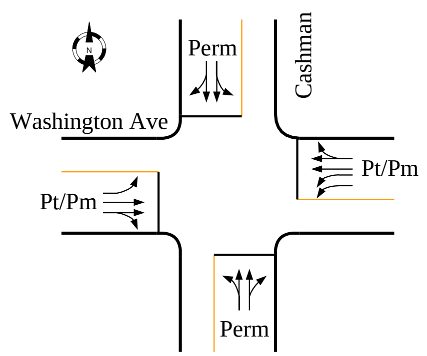
<tr><td rowspan="2">3</td><td rowspan="2">
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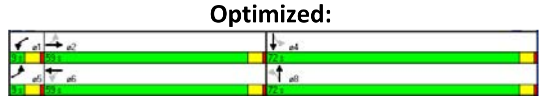
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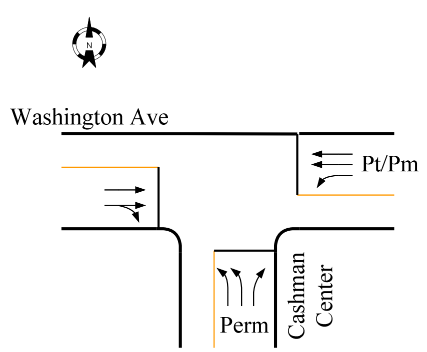
Not for Case 01 and 02</td></tr>
<tr><td rowspan="2">4</td><td rowspan="2">
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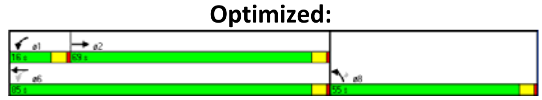
Coordinated Phase: 2, 6 (Washington Ave)
Not for Case 01 and 02</td></tr>
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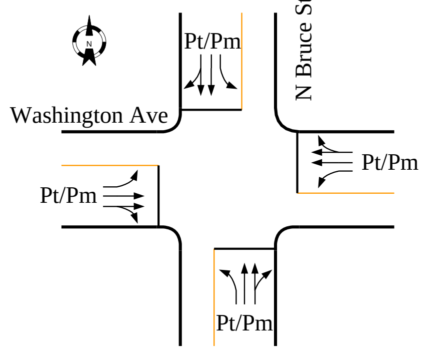
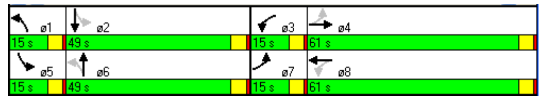
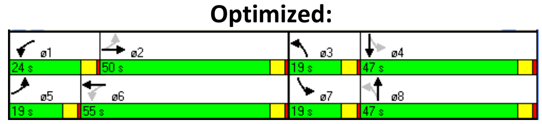
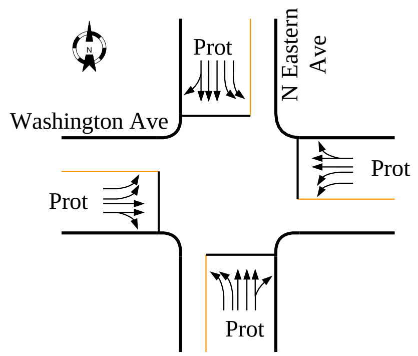
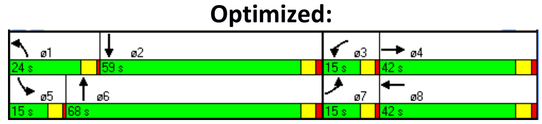
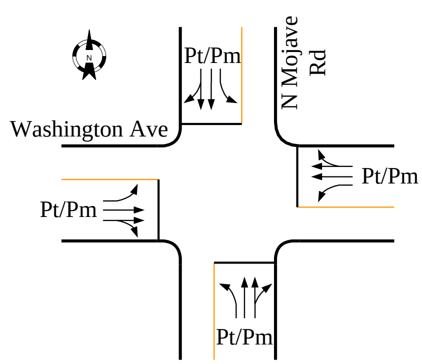
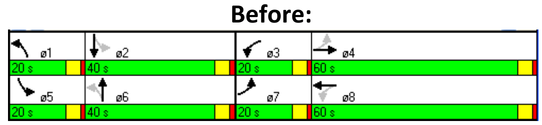
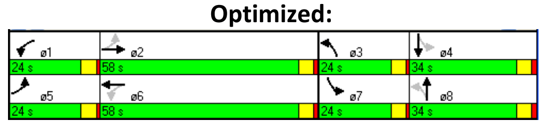
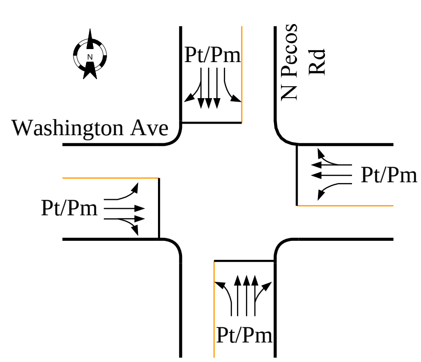
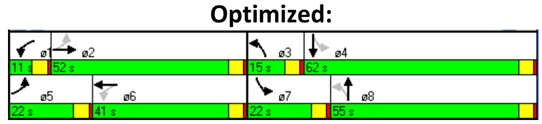
	Intersection Layout	Signal Timing Plan
5		**Before:**  Coordinated Phase: 4, 8 (Washington Ave) **Optimized:**  Coordinated Phase: 2, 6 (Washington Ave)
6		**Before:**  Coordinated Phase: 2,6 (N Eastern Ave) **Optimized:**  Coordinated Phase: 2, 6 (Washington Ave)
7		**Before:**  Coordinated Phase: 4, 8 (Washington Ave) **Optimized:**  Coordinated Phase: 2, 6 (Washington Ave)
8		**Before:** N.A. **Optimized:**  Coordinated Phase: 2, 6 (Washington Ave)

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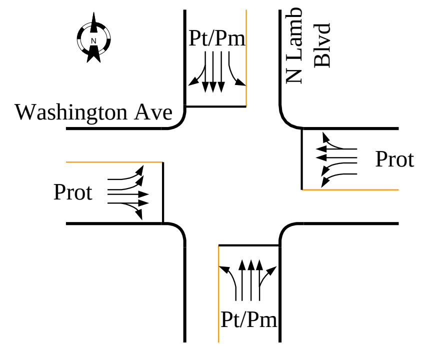
<tr><td rowspan="2">9</td><td rowspan="2">
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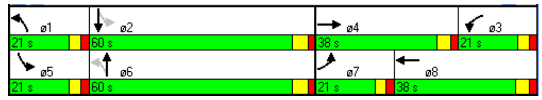
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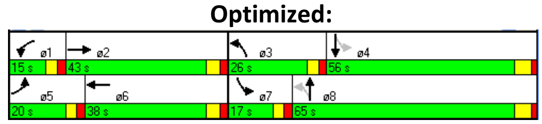
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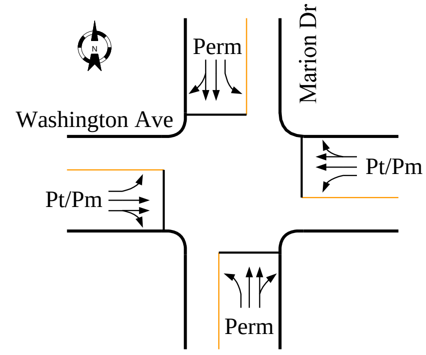
<tr><td rowspan="2">10</td><td rowspan="2">
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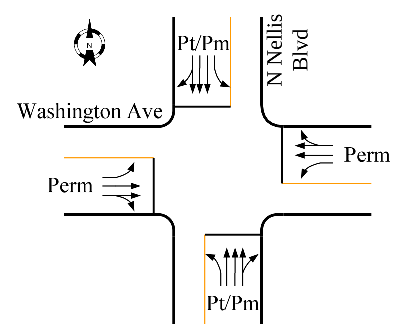
<tr><td rowspan="2">11</td><td rowspan="2">
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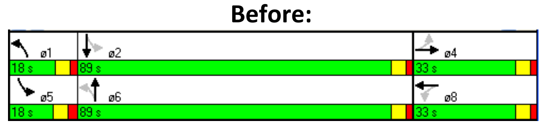
Coordinated Phase: 2, 6 (N Nellis Blvd)</td></tr>
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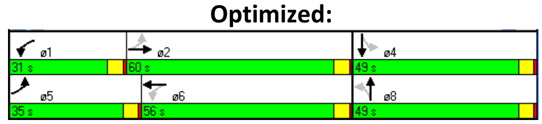

Coordinated Phase: 2, 6 (Washington Ave)</td></tr>
</table>

3.1.2 Simulation Scenarios

Table 3.1-2 shows all the simulation scenarios analyzed. There were a total of 12 scenarios generated from four cases with each case representing a specific traffic flow and network condition. As can be seen, these four cases covered a wide range of conditions that were most likely to be encountered in a real world operation. Scenarios associated with the base case represented the existing network where only the traffic demand levels varied. Scenarios associated with Case 2 represented a situation of distinctive directional flow, which was characterized by the volume of one direction significantly higher than the other direction. Signal progression generally favored the higher volume direction. Case 3 and 4 were associated with special events and nearby new developments where significantly higher demands occurred at a specific location and for specific traffic movements. The Base Scenario noted in the table indicates the scenario against which a comparison was made.

Table 3.1-2 Simulation Scenarios

	Case Description	Scenario ID	Scenario Description	Base Scenario
1	01 Base Case (Existing Network)	01-1	Low Demand (50% of PM Peak Demand)	01-3
2		01-2	Medium Low Demand (75% of PM Peak Demand)	01-3
3		01-3	Medium Demand (100% of PM Peak Demand)	-
4		01-4	Medium High Demand (120% of PM Peak Demand)	01-3
5		01-5	High Demand (150% of PM Peak Demand)	01-3
6	02 Directional Flow (Demand Doubled for EB of Washington Ave.)	02-1	Low Demand	01-1
7		02-2	Medium Low Demand	01-2
8		02-3	Medium Demand	01-3
9		02-4	Medium High Demand	01-4
10		02-5	High Demand	01-5
11	03 Special Event	03	2000vph Demand Generated by Cashman Field	-
12	04 New development	04	1200vph Demand Generated and 600vph Attracted by Cashman Field	-

3.1.3 Signal Timing Plan

ACS Lite refines parameters of the actuated coordinated signal timing plan every 5 to 10 minutes. Initial timing plans similar to time-of-day (TOD) coordination must be firstly established in its database. Based on the initial timing plans, ACS Lite can continuously monitor traffic flow and signal status, and further adjusts the signal timing accordingly. In other words, ACS Lite fine-tunes the TOD plans developed by engineers. No separate timing plans are needed. However, to operate ACS Lite with the adaptive feature, some additional parameters are needed.

For the purpose of this study, the timing plans used for the evaluation were not directly taken from the field. A new set of signal timing plans were generated by Synchro for the following reasons:

- Current signal timing plans were not optimized for progression on Washington Avenue. Several intersections had cross streets being the coordinated phases, which significantly limited the options to achieve the best progression on Washington Avenue.
- A plug-in module, referred to as a Run-Time Extension (RTE) had been developed for CORSIM so that the simulated traffic controllers in CORSIM could communicate with ACS Lite using the NTCIP protocol, which is basically similar to a real traffic controller. This RTE module made it possible to operate and evaluate ACS Lite much faster than real-time (e.g., simulating an hour of traffic in

5 minutes) using pure software-in-the-loop simulation, which was more time- and cost- efficient than obtaining and interfacing several real-traffic controllers with the CORSIM traffic simulator. However, this RTE module was fairly limited, relative to a real traffic controller. In particular, the RTE could only emulate traffic signal control with leading-left-turn phase sequencing, although ACS Lite itself was compatible with real traffic controllers using more flexible phase sequencing. Due to such a limitation with the RTE, the simulated signals were retimed with lead-left sequences (which affected two signals that would otherwise use lead-lag sequences).

- Using timing plans generated from Synchro would establish a good base for comparative study, as Synchro is probably the most widely used software for signal timing by typical traffic engineers.

Details of the signal timing plans are included in Appendix A.

3.1.4 Measures of Effectiveness (MOEs)

Four MOEs were used for the evaluation: Delay, Stopped Delay, Speed, and Travel Time per Distance Traveled. According to CORSIM's user manual, the definitions for the above four MOEs are provided below (see graphical illustrations in Figure 3.1-2):

- **Delay (seconds)**: Total delayed time in the NETSIM sub-network calculated by the actual travel time minus the ideal travel time.
- **Stopped Delay (seconds)**: The time that vehicles were stopped in the NETSIM sub-network.
- **Speed (mph)**: Average speed of vehicles travelling in the NETSIM sub-network calculated by the ratio of total travel distance and total travel time.
- **Travel Time per Distance Traveled (minutes)**: Average time for vehicles to travel one mile in the NETSIM sub-network.

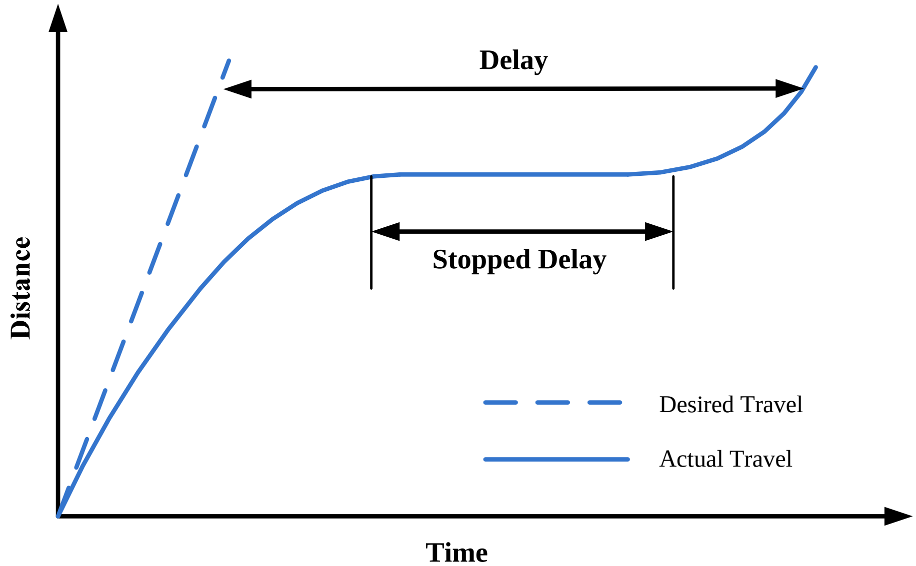


Figure 3.1-2 Illustration of Delay and Stopped Delay

3.1.5 Simulation Settings

Simulation Scheme

Using microscopic traffic simulation models generally requires multiple runs to duplicate a traffic condition and obtain reliable statistics. Ten simulation runs were implemented for each scenario in this study. A one-hour simulation time was chosen for Cases 01, 02, and 04. For Case 03 a two-hour simulation time was adopted to capture the overall performance, in which the first one hour was set to simulate the actual peak hour, and the second hour was for network clearance.

ACS Lite Settings

When the simulation platform was successfully established, ACS Lite was able to read the signal timing plans and detectors information from CORSIM automatically. The following parameters for ACS Lite were selected based on the developer's suggested values:

- Max Offset Increment: set at 4 seconds. It is defined as the amount (in seconds) by which an offset may be changed in a single adjustment.
- Max Offset Deviation: set at 20 seconds. It is defined as the maximum amount (in seconds) by which an adjusted offset may deviate from the archived baseline setting.
- Max Split Increment: set as 'Unbounded'. It is defined as the maximum amount (in seconds) by which a split may be changed in a single adjustment.
- Max Split Deviation: set as 'Unbounded'. It is defined as the maximum amount (in seconds) by which an adjusted split may deviate from the archived baseline

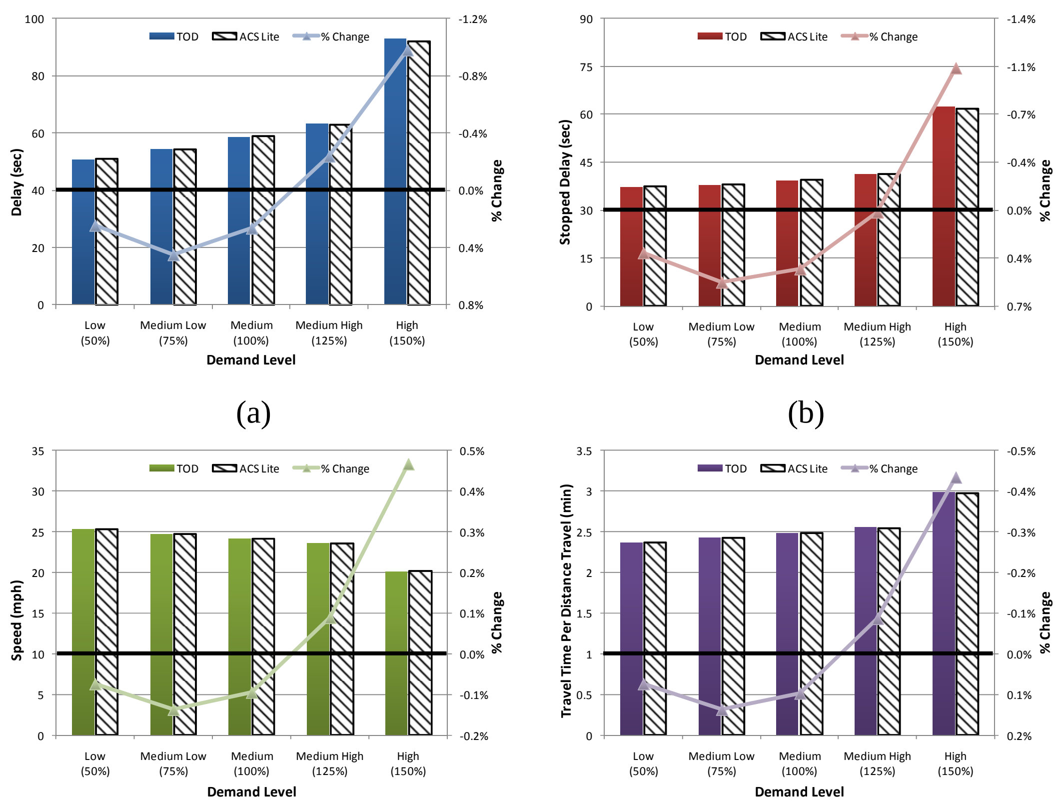
setting.

- Adjustment Interval: set at 5 minutes. It is defined as the minimum scheduled interval (in minutes) between adaptive adjustments.
- Offset Selection Method: set as 'Local'. It is defined as a method used to adjust offsets values.
- Min Offset Duration: set at 15 minutes. It is defined as the minimum time (in minutes) between changes of the traffic responsive offset selection.

3.2 Analysis Results

3.2.1 Case 01 - Base Network

The base case network (Case 01) was established based on the original Washington Avenue network. Five simulation scenarios representing different levels of traffic demand were derived based on this base case network. The intention of this case analysis was to evaluate how traffic demand level may affect ACS Lite's performance; so that guidelines can be developed on the applicability of ACS Lite based on traffic demand levels. The detailed MOEs for the two control systems (i.e., TOD and ACS Lite) are illustrated in Figure 3.2-1.



(a) (b)

(c) (d)

Figure 3.2-1 Summary of MOEs Comparison for Case 01

In the above figures, bars represent the actual MOEs values. The curved lines represent the relative improvements (in percent) by ACS Lite over TOD. The magnitude of the improvement is indicated by the secondary Y-axis (right-hand side Y-axis). The thick dark horizontal lines indicate the level of 0% improvement, i.e., any points above this line means ACS Lite worked better than TOD, while any points below the line means TOD plan worked better. Different colors were used to illustrate different MOEs.

From Figure 3.2-1, all four MOEs indicated that ACS Lite and Synchro optimized TOD plan's performances were very similar under all five demand levels. ACS Lite did not show significant improvement or deterioration. The difference between those two control systems lied within +/-1%. The detailed statistical analysis results are shown in Table 3.2-1 to Table 3.2-4.

Table 3.2-1 Statistical Analysis for Delay (Case 01)

		Mean (sec)	STDEV	% Change	Stopped Delay Improved	T-Test Significance
Low	TOD	50.65	1.39	0.2%	N	N
	ACS Lite	50.78	1.50			
Medium Low	TOD	54.16	1.24	0.4%	N	N
	ACS Lite	54.40	1.23			
Medium	TOD	58.64	1.36	0.3%	N	N
	ACS Lite	58.80	1.40			
Medium High	TOD	63.06	1.30	-0.2%	Y	N
	ACS Lite	62.91	1.54			
High	TOD	92.93	6.87	-1.0%	Y	N
	ACS Lite	92.03	7.77			

Table 3.2-2 Statistical Analysis for Stopped Delay (Case 01)

		Mean (sec)	STDEV	% Change	Stopped Delay Improved	T-Test Significance
Low	TOD	37.27	0.90	0.3%	N	N
	ACS Lite	37.38	0.92			
Medium Low	TOD	37.87	0.87	0.5%	N	N
	ACS Lite	38.07	0.83			
Medium	TOD	39.23	0.96	0.4%	N	N
	ACS Lite	39.40	0.88			
Medium High	TOD	41.14	0.83	0.0%	N	N
	ACS Lite	41.14	0.97			
High	TOD	62.43	5.22	-1.0%	Y	N
	ACS Lite	61.79	6.02			

Table 3.2-3 Statistical Analysis for Speed (Case 01)

		Mean (mph)	STDEV	% Change	Speed Improved	T-Test Significance
Low	TOD	25.32	0.14	-0.1%	N	N
	ACS Lite	25.30	0.16			
Medium Low	TOD	24.78	0.12	-0.1%	N	N
	ACS Lite	24.75	0.12			
Medium	TOD	24.14	0.12	-0.1%	N	N
	ACS Lite	24.11	0.14			
Medium High	TOD	23.53	0.13	0.1%	Y	N
	ACS Lite	23.55	0.16			
High	TOD	20.08	0.64	0.5%	Y	N
	ACS Lite	20.18	0.74			

Table 3.2-4 Statistical Analysis for Travel Time per Distance Travel (Case 01)

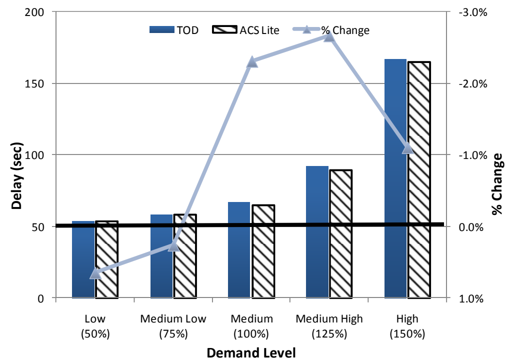
		Mean (min)	STDEV	% Change	Improved	T-Test Significance
Low	TOD	2.37	0.01	0.1%	N	N
	ACS Lite	2.37	0.02			
Medium Low	TOD	2.42	0.01	0.1%	N	N
	ACS Lite	2.42	0.01			
Medium	TOD	2.49	0.01	0.1%	N	N
	ACS Lite	2.49	0.01			
Medium High	TOD	2.55	0.01	-0.1%	Y	N
	ACS Lite	2.55	0.02			
High	TOD	2.99	0.10	-0.4%	Y	N
	ACS Lite	2.98	0.11			

The detailed statistical analysis results indicated that ACS Lite's performance in this Basic Case was very similar to the performance of the TOD plan which was obtained from Synchro's optimized timing. The t-test results also suggested no statistically different MOEs between the two control systems at the five demand levels. This may be explained by the fact that the TOD plan was already optimized and by uniformly adjusting all demands in all directions by the same percentage, there is likely little to be gained by ACS Lite from adjusting the split allocation.

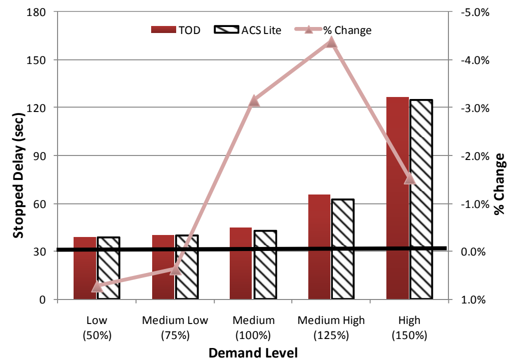
3.2.2 Case 02 - Directional Flow

The Directional Flow case was characterized by the volume of one direction significantly higher than the other direction. In most urban commute corridors, directional flow is a common traffic phenomenon in AM or PM rush hours. Signal progression generally favors the higher volume direction. This case was established to testify whether ACS Lite could automatically detect the directional traffic flow pattern and provide a better signal progression for the peak direction. The peak flow direction for this case was the eastbound on Washington Avenue.

Figure 3.2-2 illustrates the simulation results of the four MOEs for both ACS Lite and TOD controls.



(a)



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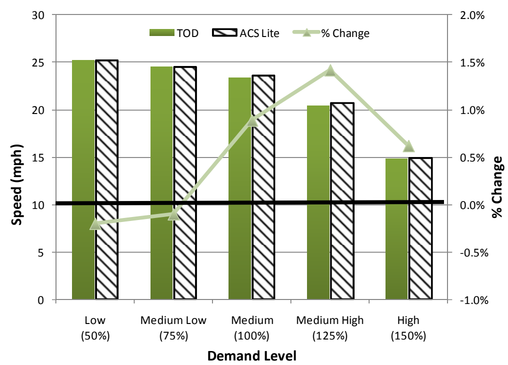

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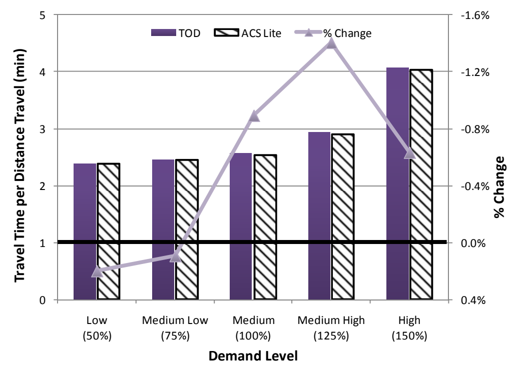

(d)

Figure 3.2-2 Summary of MOEs Comparison for Case 02

The detailed statistical analysis results are shown in Table 3.2-5 to Table 3.2-8.

Table 3.2-5 Statistical Analysis for Delay (Case 02)

		Mean (sec)	STDEV	% Change	Stopped Delay Improved	T-Test Significance
Low	TOD	53.20	1.43	0.6%	N	N
	ACS Lite	53.54	1.47			
Medium Low	TOD	57.96	1.61	0.3%	N	N
	ACS Lite	58.11	1.41			
Medium	TOD	66.49	3.41	-2.3%	Y	N
	ACS Lite	64.96	2.40			
Medium High	TOD	91.98	8.23	-2.7%	Y	N
	ACS Lite	89.52	8.05			
High	TOD	166.44	14.10	-1.1%	Y	N
	ACS Lite	164.61	13.52			

Table 3.2-6 Statistical Analysis for Stopped Delay (Case 02)

		Mean (sec)	STDEV	% Change	Stopped Delay Improved	T-Test Significance
Low	TOD	38.53	0.88	0.7%	N	N
	ACS Lite	38.81	1.01			
Medium Low	TOD	39.82	1.12	0.4%	N	N
	ACS Lite	39.96	0.91			
Medium	TOD	44.40	2.24	-3.2%	Y	Y
	ACS Lite	43.00	1.44			
Medium High	TOD	65.25	7.03	-4.4%	Y	N
	ACS Lite	62.38	6.56			
High	TOD	126.64	13.44	-1.5%	Y	N
	ACS Lite	124.69	12.40			

Table 3.2-7 Statistical Analysis for Speed (Case 02)

		Mean (mph)	STDEV	% Change	Speed Improved	T-Test Significance
Low	TOD	25.22	0.16	-0.2%	N	N
	ACS Lite	25.17	0.15			
Medium Low	TOD	24.52	0.17	-0.1%	N	N
	ACS Lite	24.50	0.15			
Medium	TOD	23.39	0.37	0.9%	Y	Y
	ACS Lite	23.60	0.25			
Medium High	TOD	20.43	0.81	1.4%	Y	N
	ACS Lite	20.72	0.79			
High	TOD	14.81	0.73	0.6%	Y	N
	ACS Lite	14.91	0.70			

Table 3.2-8 Statistical Analysis for Travel Time per Distance Travel (Case 02)

		Mean (min)	STDEV	% Change	Improved	T-Test Significance
Low	TOD	2.38	0.01	0.2%	N	N
	ACS Lite	2.38	0.01			
Medium Low	TOD	2.45	0.02	0.1%	N	N
	ACS Lite	2.45	0.02			
Medium	TOD	2.57	0.04	-0.9%	Y	Y
	ACS Lite	2.54	0.03			
Medium High	TOD	2.94	0.11	-1.4%	Y	N
	ACS Lite	2.90	0.11			
High	TOD	4.06	0.20	-0.6%	Y	N
	ACS Lite	4.03	0.19			

Again, the above results did show largely similar performance, which "on average" were insignificantly better for ACS Lite, with a few scenarios where performance measures showed statistically significant improvements with ACS Lite.

3.2.3 Case 03 - Special Events

Special events such as major sports and conventions can cause a sudden surge of traffic demands at a particular intersection and for some specific traffic movements. This case was specifically designed to simulate such special event occasions to find out how ACS Lite would react to such abnormal traffic conditions. In the study network, the nearby Cashman Field stadium often had major sports events. This special event case was created based on a simulated sport event at the stadium. A 2000 vph traffic demand was added to the Cashman Field in the first hour to simulate the stadium evacuation after the game. The second hour was introduced to simulate system recovery, 300 vehicles were added into the Cashman Field. The turning volumes used for simulating the Cashman Field special event are shown in Figure 3.2-3 for the two affected intersections. There were two intersections serving the Cashman Field: Washington Avenue/Cashman Drive on the west and Washington Avenue/Cashman Center Drive on the east. The upper two circles show the peak hour's turning volumes, and the lower two circles show the recovery hour's turning volume. The recovery hour was for clearing out the residual vehicles left in the simulation, so that the entire effect can be captured by the MOEs.

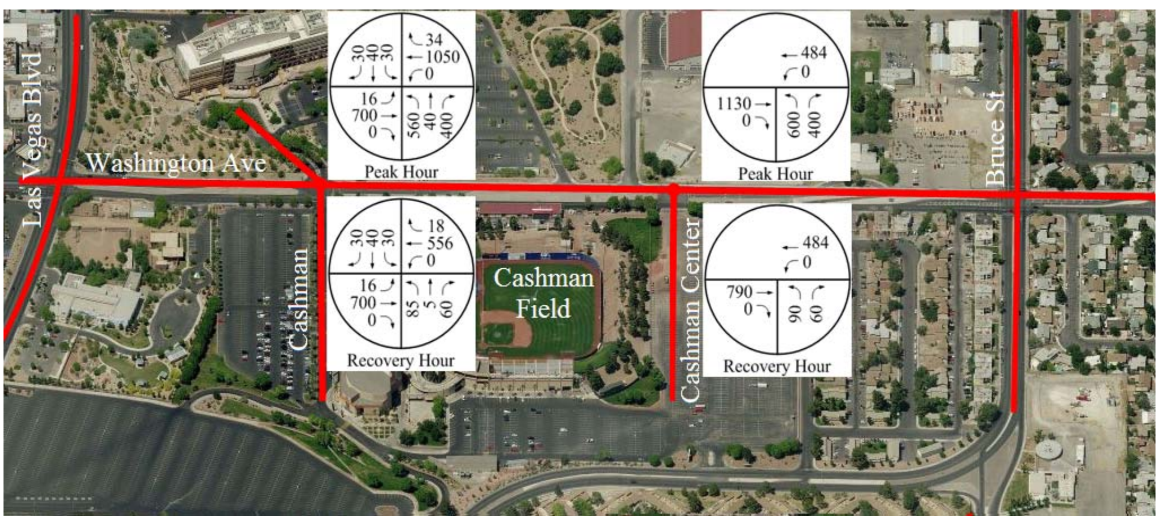

Figure 3.2-3 Turning Volumes at Cashman and Cashman Center Drive Intersections

Figure 3.2-4 illustrates the simulation results for the special event case under the Medium demand level.

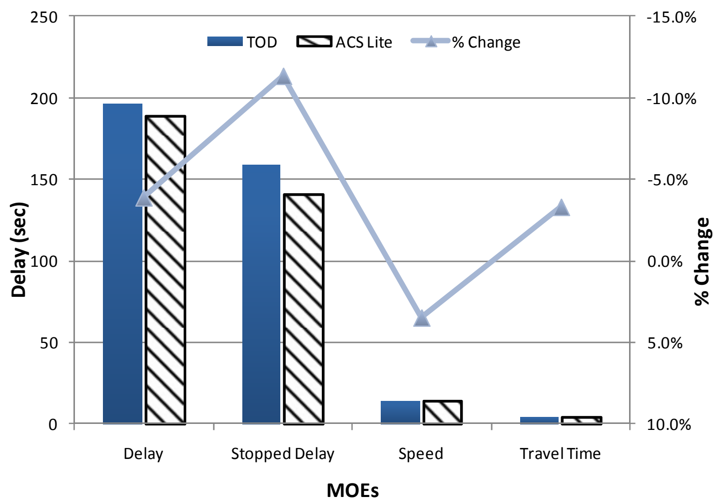

Figure 3.2-4 Summary of MOEs Comparison for Case 03

Figure 3.2-4 indicates that ACS Lite achieved better performance for all four MOEs. Delay, Stopped Delay and Travel Time per Distance Travel reduced by 3.9%, 11.3%, and 3.3%, respectively; and Speed increased by 3.5%. Compared with base Case 01, ACS Lite performed significantly better at the Medium demand level. The detailed statistical analysis results are shown in Table 3.2-9.

The t-test results showed that Delay, Stopped Delay, Speed, and Travel Time per Distance Travel had all obtained significant improvement by ACS Lite over TOD control, suggesting that ACS Lite is more effective in handling special events.

Table 3.2-9 Statistical Analysis Results (Case 03)

		Mean	STDEV	% Change	MOEs Improved	T-Test Significance
Delay	TOD	196.11	5.37	-3.9%	Y	Y
	ACS Lite	188.52	10.45			
Stopped Delay	TOD	158.38	6.01	-11.3%	Y	Y
	ACS Lite	140.42	10.46			
Speed	TOD	13.66	0.22	3.5%	Y	Y
	ACS Lite	14.14	0.50			
Travel Time	TOD	4.39	0.07	-3.3%	Y	Y
	ACS Lite	4.25	0.15			

3.2.4 Case 04 - New Development

A major new land use development near the network may significantly increase the traffic demands for particular intersection movements. Traditional TOD plan may not well adapt such traffic demand increases without a major re-timing effort, while an adaptive signal control system could benefit in such conditions. The New Development case was simulated by adding 1200 vph outbound and 600 vph inbound traffic demands at the Cashman Field site during the peak hour. The turning volumes used for the simulation at the two affected intersections (Washington/Cashman and Washington/Cashman Center) is shown in Figure 3.2-5.

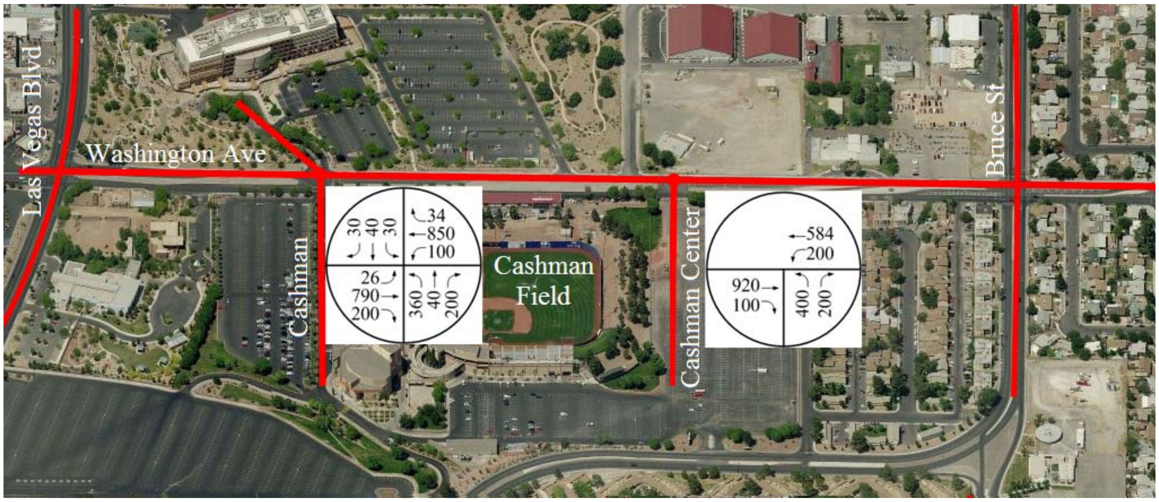

Figure 3.2-5 Simulated Turning Volumes for the New Development Case

Figure 3.2-6 illustrates the simulation results under the Medium demand level.

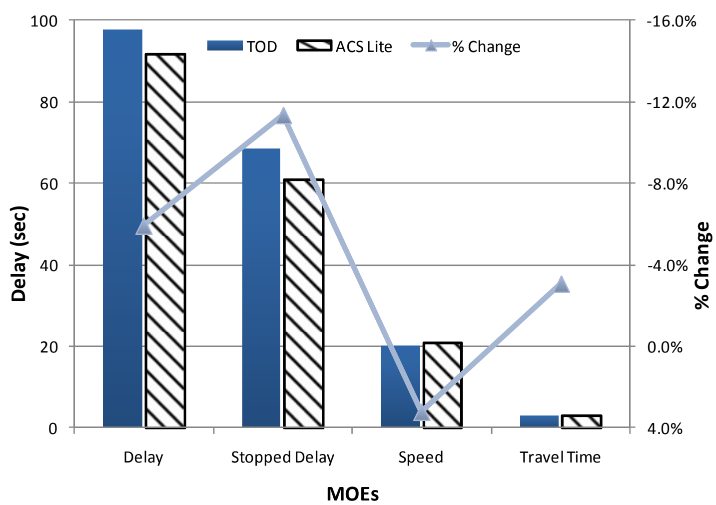

Figure 3.2-6 Summary of MOEs Comparison for Case 04

The simulation results for the New Development case were similar to that of the Special Event case. All four MOEs achieved better results under the ACS Lite's operation. Delay, Stopped Delay and Travel Time per Distance Travel reduced by 5.9%, 11.4%, and 3.1%, respectively; and Speed increased by 3.2%. Compared with the base Case 01, ACS Lite performed significantly better in this Case at the Medium demand level. The detailed statistical analysis results are shown in Table 3.2-10.

Table 3.2-10 Statistical Analysis Results (Case 04)

		Mean	STDEV	% Change	MOEs Improved	T-Test Significance
Delay	TOD	97.54	8.84	-5.9%	Y	Y
	ACS Lite	91.79	9.43			
Stopped Delay	TOD	68.53	8.48	-11.4%	Y	Y
	ACS Lite	60.75	7.07			
Speed	TOD	20.07	0.81	3.2%	Y	Y
	ACS Lite	20.71	0.88			
Travel Time	TOD	2.99	0.12	-3.1%	Y	Y
	ACS Lite	2.90	0.13			

The t-test results indicate ACS Lite achieved significantly better results in Delay, Stopped Delay, Speed, and Travel Time per Distance Travel, suggesting the ACS Lite is effective in handling traffic demand increase caused by new developments.

3.3 Summary and Findings – ACS Lite Evaluation

Evaluation of ACS Lite was primarily based on side-by-side comparisons between Synchro optimized TOD plan and ACS Lite. A total of 12 scenarios consisting of four cases at five demand levels were considered in the evaluation. For each scenario, a statistical analysis was performed to test statistical significance among the MOEs. Four major MOEs were used for the evaluation: delay, stopped delay, speed, and travel time per distance travel. The major findings are summarized as follows:

- The performance of ACS Lite and Synchro optimized actuated coordinated TOD signal timing was very similar with each other for the first two cases (base case and directional flow case). The results did not show which system performed better or worse. This result was consistent with a stated ACS Lite design principle of "do no harm".
- Although ACS Lite did not show statistically improvement over TOD, ACS Lite consistently showed better performance at the higher traffic demand situation. In our analyses, such higher traffic demand levels resembled demand exceeding capacity at the key intersections in the system.
- ACS Lite showed distinct improvement in the "Special Events" and "New Development" cases.
- The better performance of ACS Lite in the "Special Events" and "New Development" cases indicated ACS Lite can handle traffic demand increase and traffic pattern variation better than TOD plan without a major re-timing effort.
- Stopped Delay achieved the most significant improvement among all four MOEs.
- The timing plans for all the intersections were limited to the left-turn leading phase

sequence due to constraints of the interface to software emulated controllers (the limitation of the NCTIP RTE) in CORSIM, which may have restricted ACS Lite from showing its full performance potential.

4 Guidelines

One of the major objectives of this research was to develop recommendations and guidelines for implementing ATCSs in Nevada's urban areas. It is important to note that the guidelines provided in this document were only considered preliminary. The guidelines were developed based on the significant limitations noted in both Sections 2 and 3.

- An ATCS may be considered if more than one intersection in a signal network has a peak hour volume-to-capacity ratio above 1.2, which can cause high congestion of the entire network, or if growth in traffic demand is expected to push one or more intersections in the network to conditions where the volume-to-capacity ratio is greater than 1.2.
- ATCSs should not be considered if more than 80% of the intersections in a signal network have a volume-to-capacity ratio below 0.75, and no significant growth of traffic demand is expected for the next 5-10 years.
- An ATCS may be considered if significant variations of traffic demand exist at more than one location in a signal network due to cases of special events or significant changes of land use developments near the network.
- It is also important to consider the following factors before implementing an ATCS. The operational objectives must be clearly defined when making decisions on implementing ATCSs. ATCSs tend to achieve balanced service for all vehicle movements, thus minimizing delay tends to be of higher priority than minimizing arterial stops.
- A reliable detection system should be in place for an ATCS to achieve the expected performance. Signal systems of large intersections with video detection systems may impose major limitations to camera setup and detector layout unless more cameras can be deployed to have an adequate coverage of the detection areas.
- A reliable communication system should also be in place for an ATCS. While not modeled specifically, interrupted communications will force intersections to run in a less than optimal plan, and may disrupt coordination if communications are not operational for an extended length of time.
- Easiness of system setup and parameter modification seems to be a major factor affecting an agency's decision. The agency needs to understand that any adaptive system will be different from what they are used to operating and maintaining, and to be both prepared for the time that it will take to learn how to effectively manage it, as well as be prepared to contact the system provider with any questions, as not every scenario can be trained for.

5 Summary and Conclusions

The Regional Transportation Commission of Southern Nevada (RTCSN) and the Nevada Department of Transportation (NDOT) sponsored this research project to conduct comprehensive evaluations on Adaptive Traffic Control Systems (ATCSs). It was expected that the outcome of the study will produce recommendations and guidance for ATCSs from the benefit-cost perspective, thus strategic decisions can be made on whether more adaptive systems should be deployed in Nevada's urban areas. Various traffic and signal system conditions were thoroughly analyzed using microscopic traffic simulation models running with virtual adaptive signal control algorithms. The analyses involved two ATCSs: SCATS and ACS Lite. Some preliminary guidelines were developed for ATCS implementations based on the results and findings from the simulation analyses.

5.1 Summary of Major Findings

SCATS

The SCATS evaluation involved a total of 27 scenarios which were classified into seven different cases under five demand levels. Major findings from the evaluation are summarized as follows:

- Based on the Network Level MOEs, SCATS consistently showed better performance at the higher traffic demand levels than TOD control. In our analyses, such higher traffic demand levels resembled demand exceeding capacity at the key intersections in the system. SCATS did not show any improvement under low and medium demand levels.
- For the Node Level performance, SCATS was good at balancing the delays and queues at the critical intersections. It was more evident at the Medium High and High demand levels. However, for the Route Level performance, SCATS did not show any advantage over TOD control. This was because SCATS treated the major street and minor street equally to obtain the overall network optimization while the TOD plans tended to favor main street movements and coordination.
- SCATS achieved better results in minimizing delays than stops. Therefore, the higher number of stops may be an indication of less optimal progression, which could be enhanced through its operating algorithm or modifying the objective functions in the SCATS setup.
- SCATS showed better performance for the "New Development" case, suggesting that SCATS can better handle significant traffic demand growth than TOD plan without a major re-timing effort. However, mixed results were observed for other special cases. For the "Special Event" case, SCATS did not show any improvement. For the "Directional Flow" cases, SCATS showed improvement only at the Medium High or High demand levels. Some "Detector Failures" did not show a significant impact on SCATS performance, but when the detectors on both major and minor streets failed, SCATS performed poorly.

- The performance of any SCATS installation, and therefore the SCATS algorithms, are significantly a function of several factors, including the characteristics of the underlying traffic control configuration within SCATS, the objectives of that configuration, and the expected operating traffic conditions. The less satisfactory results under the low and medium demand levels seemed to be contributed by the minimum cycle time setup in SCATS. This minimum cycle time was due to constraints of pedestrians crossing the very wide main street, which is not common at typical urban arterials. A lower minimum cycle time would perhaps be more suitable for the lower and medium demand levels simulated, but the experiment was not carried out due to time constraints.

- Some major limitations were noted and may have contributed to SCATS non-optimal performance under some cases. One was related to video detection issues and the other was related to the highly congested triangle area of the network. Use of video detection at the network signals placed significant constraints to where detection zones needed to be drawn. In many cases, the number and location of the detectors could not be placed ideally. The same constraints applied to the simulation setup because of a direction adoption of the field database. The other limitation was the rigid setup by RTC/FAST engineers at the triangle area which did not give much flexibility for SCATS to adapt.

- It should also be noted that SCATS was compared with a highly optimized TOD plan under the general cases. A highly optimized TOD plan developed based on specific traffic conditions is expected to perform better than any adaptive traffic control systems. However, TOD plan will deteriorate over time, but adaptive systems such as SCATS can prolong over a longer time period as evidenced by the results under the high traffic demand levels.

ACS Lite

Following a similar study scheme, evaluation of ACS Lite resulted in the below major findings and conclusions:

- ACS Lite and the optimized actuated coordinated TOD signal timing showed very similar performance under normal traffic conditions. The results did not show which system performed better or worse, which was consistent with a stated ACS Lite design principle of "do no harm".
- ACS Lite showed better performance at higher demand levels and under sudden demand increase situations, such as the "Special Events" and "New Development" cases. This result suggested that ACS Lite can better handle traffic demand increase and flow variation than TOD plan.
- The performance potential of ACS Lite system may have not been evaluated thoroughly, because the timing plan configurations were significantly restricted by the software interface in CORSIM. One particular example was that the virtual ACS Lite was limited to leading left-turn phasing only.

General

Some general findings and conclusions related to the two ATCSs are provided next:

- The ATCSs consistently showed improved performance over the time-of-day timing plans at high traffic demand levels. In our analyses, such high traffic demand levels resembled demand exceeding capacity at some key intersections in the system. However, in most cases, the improvement was not statistically significant based on the selected performance measures.
- The ATCSs did not show significant improvement when the majority of the intersections in a system had low demand levels. In our analyses, such low demand levels resembled volume-to-capacity ratios lower than 0.75.
- The ATCSs showed no or minor improvements over the TOD timing plans under "Special Events" and "New Developments" cases when significant demand increase occurred at selected intersections and for specific traffic movements.
- Reliable detection is a key element for the ATCSs to achieve the expected performance. It generally requires abundant knowledge and technical skills to set up an ATCS. System maintenance and parameter modifications would also require major efforts from well-trained engineering staff.

5.2 Guidelines

One of the objectives of this research was to develop recommendations and guidelines for implementing ATCSs in Nevada's urban areas. It is important to note that the guidelines provided in this document were only considered preliminary. The guidelines were developed based on the significant limitations noted in both Sections 2 and 3.

- An ATCS may be considered if more than one intersection in a signal network has a peak hour volume-to-capacity ratio above 1.2, which can cause high congestion of the entire network, or if growth in traffic demand is expected to push one or more intersections in the network to conditions where the volume-to-capacity ratio is greater than 1.2.
- ATCSs should not be considered if more than 80 percent of the intersections in a signal network have a volume-to-capacity ratio below 0.75, and no significant growth of traffic demand is expected for the next 5-10 years.
- An ATCS may be considered if significant variations of traffic demand exist at more than one location in a signal network due to cases of special events or significant changes of land use developments near the network.
- It is also important to consider the following factors before implementing an ATCS. The operational objectives must be clearly defined when making decisions on implementing ATCSs. ATCSs tend to achieve balanced service for all vehicle movements, thus minimizing delay tends to be of higher priority than minimizing arterial stops.
- A reliable detection system should be in place for an ATCS to achieve the expected performance. Signal systems of large intersections with video detection

systems may impose major limitations to camera setup and detector layout unless more cameras can be deployed to have an adequate coverage of the detection areas.

- A reliable communication system should also be in place for an ATCS. While not modeled specifically, interrupted communications will force intersections to run in a less than optimal plan, and may disrupt coordination if communications are not operational for an extended length of time.
- Easiness of system setup and parameter modification seems to be a major factor affecting an agency's decision. The agency needs to understand that any adaptive system will be different from what they are used to operating and maintaining, and to be both prepared for the time that it will take to learn how to effectively manage it, as well as be prepared to contact the system provider with any questions, as not every scenario can be trained for.

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Appendix A. Synchro Optimized Signal Timing Plan

Signal Timing Plan 1: Base Signal Timing Plan

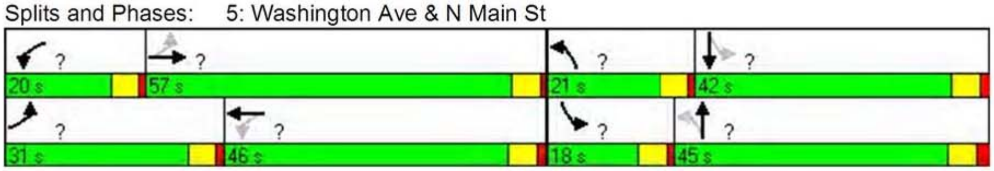
Lanes, Volumes, Timings
5: Washington Ave & N Main St 2010-5-20

Lane Group	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Lane Configurations	↰	↑↑		↰	↑↑		↰	↑↑		↰	↑↑	
Ideal Flow (vphpl)	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900
Total Lost Time (s)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Leading Detector (ft)	49	49		49	49		49	49		49	49	
Trailing Detector (ft)	0	0		0	0		0	0		0	0	
Turning Speed (mph)	16		9	16		9	16		9	16		9
Right Turn on Red			Yes			Yes			Yes			Yes
Link Speed (mph)		35			35			30			30	
Link Distance (ft)		1097			1851			1509			1923	
Travel Time (s)		21.4			36.1			34.3			43.7	
Volume (vph)	244	565	108	23	411	106	128	464	43	96	428	76
Peak Hour Factor	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Turn Type	pm+pt			pm+pt			pm+pt			pm+pt		
Protected Phases	5	2		1	6		3	8		7	4	
Permitted Phases	2			6			8			4		
Detector Phases	5	2		1	6		3	8		7	4	
Minimum Initial (s)	4.0	8.0		4.0	8.0		4.0	10.0		4.0	10.0	
Minimum Split (s)	16.0	44.0		16.0	44.0		14.0	38.0		14.0	38.0	
Total Split (s)	31.0	57.0	0.0	20.0	46.0	0.0	21.0	45.0	0.0	18.0	42.0	0.0
Total Split (%)	22.1%	40.7%	0.0%	14.3%	32.9%	0.0%	15.0%	32.1%	0.0%	12.9%	30.0%	0.0%
Maximum Green (s)	26.0	52.0		15.0	40.5		16.0	39.0		13.0	36.5	
Yellow Time (s)	4.0	4.0		4.0	4.0		4.0	4.0		4.0	4.0	
All-Red Time (s)	1.0	1.0		1.0	1.5		1.0	2.0		1.0	1.5	
Lead/Lag	Lead	Lag		Lead	Lag		Lead	Lag		Lead	Lag	
Lead-Lag Optimize?												
Vehicle Extension (s)	3.0	3.0		3.0	3.0		3.0	3.0		3.0	3.0	
Recall Mode	None	C-Min		None	C-Min		None	None		None	None	
Walk Time (s)		7.0			7.0			7.0			7.0	
Flash Dont Walk (s)		18.0			18.0			14.0			14.0	
Pedestrian Calls (#/hr)		0			0			0			0	

Intersection Summary

Area Type: Other
Cycle Length: 140
Actuated Cycle Length: 140
Offset: 80 (57%), Referenced to phase 2:EBTL and 6:WBTL, Start of Red
Natural Cycle: 115
Control Type: Actuated-Coordinated

Splits and Phases: 5: Washington Ave & N Main St



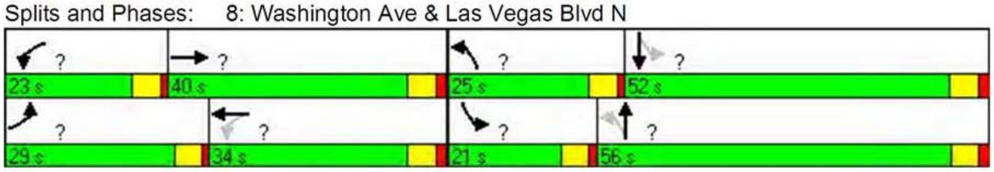
Lanes, Volumes, Timings
8: Washington Ave & Las Vegas Blvd N 2010-5-20

Lane Group	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Lane Configurations												
Ideal Flow (vphpl)	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900
Total Lost Time (s)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Leading Detector (ft)	49	49		49	49		49	49		49	49	
Trailing Detector (ft)	0	0		0	0		0	0		0	0	
Turning Speed (mph)	16		9	16		9	16		9	16		9
Right Turn on Red			Yes			Yes			Yes			Yes
Link Speed (mph)		35			35			35			35	
Link Distance (ft)		1851			2661			1804			1594	
Travel Time (s)		36.1			51.8			35.1			31.1	
Volume (vph)	136	492	76	124	344	16	164	680	164	60	488	32
Peak Hour Factor	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Turn Type	Prot			pm+pt			pm+pt			pm+pt		
Protected Phases	5	2		1	6		3	8		7	4	
Permitted Phases				6			8			4		
Detector Phases	5	2		1	6		3	8		7	4	
Minimum Initial (s)	4.0	4.0		4.0	4.0		4.0	4.0		4.0	4.0	
Minimum Split (s)	16.0	30.0		16.0	30.0		20.0	49.0		16.0	45.0	
Total Split (s)	29.0	40.0	0.0	23.0	34.0	0.0	25.0	56.0	0.0	21.0	52.0	0.0
Total Split (%)	20.7%	28.6%	0.0%	16.4%	24.3%	0.0%	17.9%	40.0%	0.0%	15.0%	37.1%	0.0%
Maximum Green (s)	24.0	34.2		18.0	28.2		20.0	50.3		16.0	46.2	
Yellow Time (s)	4.0	4.0		4.0	4.0		4.0	4.0		4.0	4.0	
All-Red Time (s)	1.0	1.8		1.0	1.8		1.0	1.7		1.0	1.8	
Lead/Lag	Lead	Lag		Lead	Lag		Lead	Lag		Lead	Lag	
Lead-Lag Optimize?												
Vehicle Extension (s)	3.0	3.0		3.0	3.0		3.0	3.0		3.0	3.0	
Recall Mode	None	C-Min		None	C-Min		None	None		None	Min	
Walk Time (s)		7.0			7.0			7.0			7.0	
Flash Dont Walk (s)		11.0			11.0			11.0			11.0	
Pedestrian Calls (#/hr)		0			0			0			0	

Intersection Summary

Area Type: Other
Cycle Length: 140
Actuated Cycle Length: 140
Offset: 119 (85%), Referenced to phase 2:EBT and 6:WBTL, Start of Red
Natural Cycle: 115
Control Type: Actuated-Coordinated

Splits and Phases: 8: Washington Ave & Las Vegas Blvd N

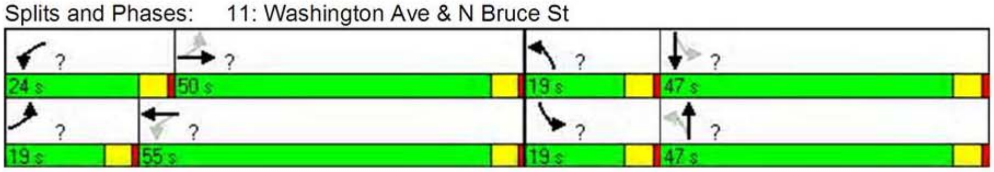


Lanes, Volumes, Timings
11: Washington Ave & N Bruce St   2010-5-20

Lane Group	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Lane Configurations	↰	↑↑		↰	↑↑		↰	↑↑		↰	↑↑	
Ideal Flow (vphpl)	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900
Total Lost Time (s)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Leading Detector (ft)	49	49		49	49		49	49		49	49	
Trailing Detector (ft)	0	0		0	0		0	0		0	0	
Turning Speed (mph)	16		9	16		9	16		9	16		9
Right Turn on Red			Yes			Yes			Yes			Yes
Link Speed (mph)		35			35			35			35	
Link Distance (ft)		845			2669			1788			1602	
Travel Time (s)		16.5			52.0			34.8			31.2	
Volume (vph)	52	622	42	120	384	44	48	444	151	43	348	52
Peak Hour Factor	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Turn Type	pm+pt			pm+pt			pm+pt			pm+pt		
Protected Phases	5	2		1	6		3	8		7	4	
Permitted Phases	2			6			8			4		
Detector Phases	5	2		1	6		3	8		7	4	
Minimum Initial (s)	4.0	4.0		4.0	4.0		4.0	4.0		4.0	4.0	
Minimum Split (s)	12.0	45.0		12.0	45.0		12.0	40.0		12.0	40.0	
Total Split (s)	19.0	50.0	0.0	24.0	55.0	0.0	19.0	47.0	0.0	19.0	47.0	0.0
Total Split (%)	13.6%	35.7%	0.0%	17.1%	39.3%	0.0%	13.6%	33.6%	0.0%	13.6%	33.6%	0.0%
Maximum Green (s)	14.0	45.0		19.0	50.0		14.0	41.7		14.0	41.7	
Yellow Time (s)	4.0	4.0		4.0	4.0		4.0	4.0		4.0	4.0	
All-Red Time (s)	1.0	1.0		1.0	1.0		1.0	1.3		1.0	1.3	
Lead/Lag	Lead	Lag		Lead	Lag		Lead	Lag		Lead	Lag	
Lead-Lag Optimize?												
Vehicle Extension (s)	3.0	3.0		3.0	3.0		3.0	3.0		3.0	3.0	
Recall Mode	None	C-Min		None	C-Min		None	Min		None	Min	
Walk Time (s)		7.0			7.0			7.0			7.0	
Flash Dont Walk (s)		11.0			11.0			11.0			11.0	
Pedestrian Calls (#/hr)		0			0			0			0	

Intersection Summary
Area Type: Other
Cycle Length: 140
Actuated Cycle Length: 140
Offset: 38 (27%), Referenced to phase 2:EBTL and 6:WBTL, Start of Red
Natural Cycle: 110
Control Type: Actuated-Coordinated

Splits and Phases: 11: Washington Ave & N Bruce St



Lanes, Volumes, Timings

14: Washington Ave & N Eastern Ave

2010-5-20

Lane Group	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Lane Configurations	↰↰	↑↑		↰↰	↑↑		↰↰	↑↑↑		↰↰	↑↑↑	
Ideal Flow (vphpl)	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900
Total Lost Time (s)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Leading Detector (ft)	49	49		49	49		49	49		49	49	
Trailing Detector (ft)	0	0		0	0		0	0		0	0	
Turning Speed (mph)	16		9	16		9	16		9	16		9
Right Turn on Red			Yes			Yes			Yes			Yes
Link Speed (mph)		35			35			35			35	
Link Distance (ft)		2669			2608			1924			1610	
Travel Time (s)		52.0			50.8			37.5			31.4	
Volume (vph)	148	544	125	160	374	84	108	1376	228	108	1408	66
Peak Hour Factor	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Turn Type	Prot			Prot			Prot			Prot		
Protected Phases	7	4		3	8		1	6		5	2	
Permitted Phases												
Detector Phases	7	4		3	8		1	6		5	2	
Minimum Initial (s)	4.0	4.0		4.0	4.0		4.0	4.0		4.0	4.0	
Minimum Split (s)	15.0	25.0		15.0	28.0		24.0	54.0		15.0	45.0	
Total Split (s)	15.0	42.0	0.0	15.0	42.0	0.0	24.0	68.0	0.0	15.0	59.0	0.0
Total Split (%)	10.7%	30.0%	0.0%	10.7%	30.0%	0.0%	17.1%	48.6%	0.0%	10.7%	42.1%	0.0%
Maximum Green (s)	10.0	36.2		10.0	36.2		19.0	62.2		10.0	53.2	
Yellow Time (s)	4.0	4.0		4.0	4.0		4.0	4.0		4.0	4.0	
All-Red Time (s)	1.0	1.8		1.0	1.8		1.0	1.8		1.0	1.8	
Lead/Lag	Lead	Lag		Lead	Lag		Lead	Lag		Lead	Lag	
Lead-Lag Optimize?	Yes	Yes		Yes	Yes		Yes	Yes		Yes	Yes	
Vehicle Extension (s)	3.0	3.0		3.0	3.0		3.0	3.0		3.0	3.0	
Recall Mode	None	Min		None	Min		None	C-Min		None	C-Min	
Walk Time (s)		7.0			7.0			7.0			7.0	
Flash Dont Walk (s)		11.0			11.0			11.0			11.0	
Pedestrian Calls (#/hr)		0			0			0			0	

Intersection Summary

Area Type: Other

Cycle Length: 140

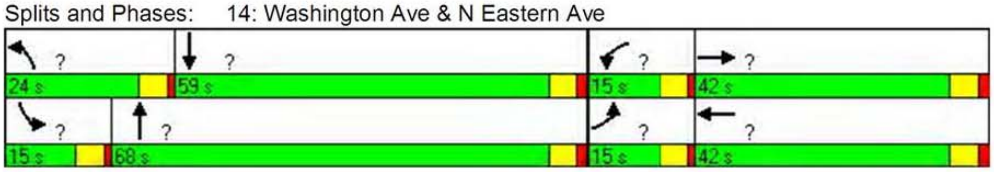
Actuated Cycle Length: 140

Offset: 22 (16%), Referenced to phase 2:SBT and 6:NBT, Start of Red

Natural Cycle: 115

Control Type: Actuated-Coordinated

Splits and Phases: 14: Washington Ave & N Eastern Ave

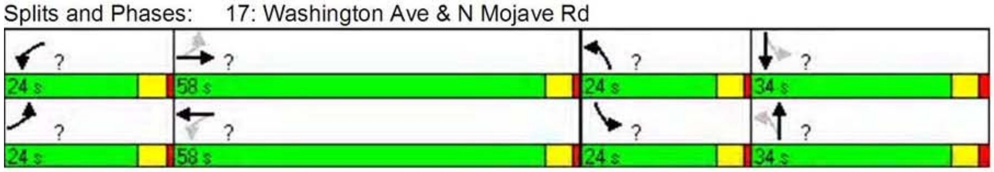


Lanes, Volumes, Timings
17: Washington Ave & N Mojave Rd 2010-5-20

Lane Group	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Lane Configurations	↰	↑↑		↰	↑↑		↰	↑↑		↰	↑↑	
Ideal Flow (vphpl)	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900
Total Lost Time (s)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Leading Detector (ft)	49	49		49	49		49	49		49	49	
Trailing Detector (ft)	0	0		0	0		0	0		0	0	
Turning Speed (mph)	16		9	16		9	16		9	16		9
Right Turn on Red			Yes			Yes			Yes			Yes
Link Speed (mph)		35			35			25			25	
Link Distance (ft)		2608			2650			1970			1604	
Travel Time (s)		50.8			51.6			53.7			43.7	
Volume (vph)	101	717	63	72	506	68	68	228	68	40	136	44
Peak Hour Factor	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Turn Type	pm+pt			pm+pt			pm+pt			pm+pt		
Protected Phases	5	2		1	6		3	8		7	4	
Permitted Phases	2			6			8			4		
Detector Phases	5	2		1	6		3	8		7	4	
Minimum Initial (s)	4.0	4.0		4.0	4.0		4.0	4.0		4.0	4.0	
Minimum Split (s)	15.0	40.0		15.0	40.0		15.0	25.0		15.0	25.0	
Total Split (s)	24.0	58.0	0.0	24.0	58.0	0.0	24.0	34.0	0.0	24.0	34.0	0.0
Total Split (%)	17.1%	41.4%	0.0%	17.1%	41.4%	0.0%	17.1%	24.3%	0.0%	17.1%	24.3%	0.0%
Maximum Green (s)	19.0	52.7		19.0	52.7		19.0	28.4		19.0	28.4	
Yellow Time (s)	4.0	4.0		4.0	4.0		4.0	4.0		4.0	4.0	
All-Red Time (s)	1.0	1.3		1.0	1.3		1.0	1.6		1.0	1.6	
Lead/Lag	Lead	Lag		Lead	Lag		Lead	Lag		Lead	Lag	
Lead-Lag Optimize?												
Vehicle Extension (s)	3.0	3.0		3.0	3.0		3.0	3.0		3.0	3.0	
Recall Mode	None	C-Max		None	C-Max		None	Min		None	Min	
Walk Time (s)		7.0			7.0			7.0			7.0	
Flash Dont Walk (s)		11.0			11.0			11.0			11.0	
Pedestrian Calls (#/hr)		0			0			0			0	

Intersection Summary	
Area Type:	Other
Cycle Length: 140	
Actuated Cycle Length: 140	
Offset: 16 (11%), Referenced to phase 2:EBTL and 6:WBTL, Start of Red	
Natural Cycle: 95	
Control Type: Actuated-Coordinated	

Splits and Phases: 17: Washington Ave & N Mojave Rd



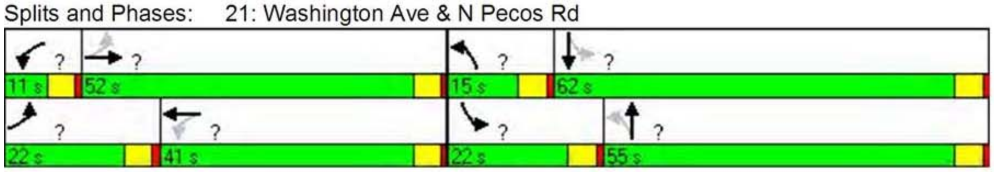
Lanes, Volumes, Timings
21: Washington Ave & N Pecos Rd 2010-5-20

Lane Group	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Lane Configurations	↰	↑↑		↰	↑↑		↰	↑↑↑		↰	↑↑↑	
Ideal Flow (vphpl)	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900
Total Lost Time (s)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Leading Detector (ft)	49	49		49	49		49	49		49	49	
Trailing Detector (ft)	0	0		0	0		0	0		0	0	
Turning Speed (mph)	16		9	16		9	16		9	16		9
Right Turn on Red			Yes			Yes			Yes			Yes
Link Speed (mph)		35			35			45			35	
Link Distance (ft)		2650			5292			1836			1698	
Travel Time (s)		51.6			103.1			27.8			33.1	
Volume (vph)	154	593	77	64	480	116	133	1208	136	136	720	33
Peak Hour Factor	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Turn Type	pm+pt			pm+pt			pm+pt			pm+pt		
Protected Phases	5	2		1	6		3	8		7	4	
Permitted Phases	2			6			8			4		
Detector Phases	5	2		1	6		3	8		7	4	
Minimum Initial (s)	4.0	4.0		4.0	4.0		4.0	4.0		4.0	4.0	
Minimum Split (s)	9.0	23.0		9.0	23.0		9.0	23.0		9.0	23.0	
Total Split (s)	22.0	52.0	0.0	11.0	41.0	0.0	15.0	55.0	0.0	22.0	62.0	0.0
Total Split (%)	15.7%	37.1%	0.0%	7.9%	29.3%	0.0%	10.7%	39.3%	0.0%	15.7%	44.3%	0.0%
Maximum Green (s)	17.0	47.0		6.0	36.0		10.0	50.0		17.0	57.0	
Yellow Time (s)	4.0	4.0		4.0	4.0		4.0	4.0		4.0	4.0	
All-Red Time (s)	1.0	1.0		1.0	1.0		1.0	1.0		1.0	1.0	
Lead/Lag	Lead	Lag		Lead	Lag		Lead	Lag		Lead	Lag	
Lead-Lag Optimize?												
Vehicle Extension (s)	3.0	3.0		3.0	3.0		3.0	3.0		3.0	3.0	
Recall Mode	None	C-Max		None	C-Max		None	Min		None	Min	
Walk Time (s)		7.0			7.0			7.0			7.0	
Flash Dont Walk (s)		11.0			11.0			11.0			11.0	
Pedestrian Calls (#/hr)		0			0			0			0	

Intersection Summary

Area Type: Other
Cycle Length: 140
Actuated Cycle Length: 140
Offset: 64 (46%), Referenced to phase 2:EBTL and 6:WBTL, Start of Red
Natural Cycle: 65
Control Type: Actuated-Coordinated

Splits and Phases: 21: Washington Ave & N Pecos Rd

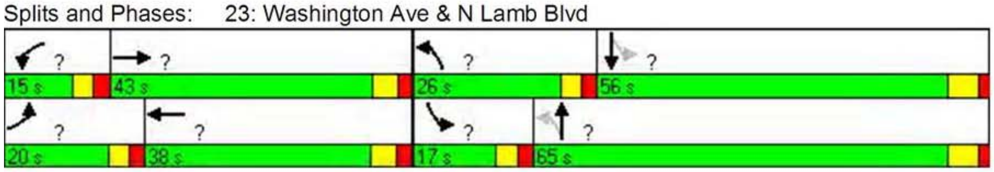


Lanes, Volumes, Timings
23: Washington Ave & N Lamb Blvd 2010-5-20

Lane Group	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Lane Configurations												
Ideal Flow (vphpl)	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900
Total Lost Time (s)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Leading Detector (ft)	49	49		49	49		49	49		49	49	
Trailing Detector (ft)	0	0		0	0		0	0		0	0	
Turning Speed (mph)	16		9	16		9	16		9	16		9
Right Turn on Red			Yes			Yes			Yes			Yes
Link Speed (mph)		35			35			45			31	
Link Distance (ft)		5292			2726			1835			1728	
Travel Time (s)		103.1			53.1			27.8			38.0	
Volume (vph)	230	460	176	164	336	108	200	1296	80	108	1324	123
Peak Hour Factor	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Turn Type	Prot			Prot			pm+pt			pm+pt		
Protected Phases	5	2		1	6		3	8		7	4	
Permitted Phases							8			4		
Detector Phases	5	2		1	6		3	8		7	4	
Minimum Initial (s)	4.0	4.0		4.0	4.0		4.0	4.0		4.0	4.0	
Minimum Split (s)	15.0	25.0		15.0	25.0		15.0	50.0		15.0	50.0	
Total Split (s)	20.0	43.0	0.0	15.0	38.0	0.0	26.0	65.0	0.0	17.0	56.0	0.0
Total Split (%)	14.3%	30.7%	0.0%	10.7%	27.1%	0.0%	18.6%	46.4%	0.0%	12.1%	40.0%	0.0%
Maximum Green (s)	14.8	37.2		9.7	32.1		20.9	58.9		11.8	49.9	
Yellow Time (s)	3.0	3.6		3.0	3.6		3.0	4.3		3.0	4.3	
All-Red Time (s)	2.2	2.2		2.3	2.3		2.1	1.8		2.2	1.8	
Lead/Lag	Lead	Lag		Lead	Lag		Lead	Lag		Lead	Lag	
Lead-Lag Optimize?	Yes	Yes		Yes	Yes							
Vehicle Extension (s)	3.0	3.0		3.0	3.0		3.0	3.0		3.0	3.0	
Recall Mode	None	C-Min		None	C-Min		None	None		None	None	
Walk Time (s)		7.0			7.0			7.0			7.0	
Flash Dont Walk (s)		11.0			11.0			11.0			11.0	
Pedestrian Calls (#/hr)		0			0			0			0	

Intersection Summary
Area Type: Other
Cycle Length: 140
Actuated Cycle Length: 140
Offset: 45 (32%), Referenced to phase 2:EBT and 6:WBT, Start of Red
Natural Cycle: 105
Control Type: Actuated-Coordinated

Splits and Phases: 23: Washington Ave & N Lamb Blvd



Lanes, Volumes, Timings
26: Washington Ave & Marion Dr

2010-5-20

Lane Group	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Lane Configurations	↰	↑↑		↰	↑↑		↰	↑↑		↰	↑↑	
Ideal Flow (vphpl)	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900
Total Lost Time (s)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Leading Detector (ft)	49	49		49	49		49	49		49	49	
Trailing Detector (ft)	0	0		0	0		0	0		0	0	
Turning Speed (mph)	16		9	16		9	16		9	16		9
Right Turn on Red			Yes			Yes			Yes			Yes
Link Speed (mph)		35			35			25			31	
Link Distance (ft)		2726			2643			951			1710	
Travel Time (s)		53.1			51.5			25.9			37.6	
Volume (vph)	72	508	68	12	437	36	105	72	20	12	60	67
Peak Hour Factor	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Turn Type	pm+pt			pm+pt			Perm			Perm		
Protected Phases	5	2		1	6			8			4	
Permitted Phases	2			6			8			4		
Detector Phases	5	2		1	6		8	8		4	4	
Minimum Initial (s)	4.0	4.0		4.0	4.0		4.0	4.0		4.0	4.0	
Minimum Split (s)	9.0	23.0		9.0	23.0		23.0	23.0		23.0	23.0	
Total Split (s)	35.0	60.0	0.0	31.0	56.0	0.0	49.0	49.0	0.0	49.0	49.0	0.0
Total Split (%)	25.0%	42.9%	0.0%	22.1%	40.0%	0.0%	35.0%	35.0%	0.0%	35.0%	35.0%	0.0%
Maximum Green (s)	30.0	55.0		26.0	51.0		44.0	44.0		44.0	44.0	
Yellow Time (s)	4.0	4.0		4.0	4.0		4.0	4.0		4.0	4.0	
All-Red Time (s)	1.0	1.0		1.0	1.0		1.0	1.0		1.0	1.0	
Lead/Lag	Lead	Lag		Lead	Lag							
Lead-Lag Optimize?												
Vehicle Extension (s)	3.0	3.0		3.0	3.0		3.0	3.0		3.0	3.0	
Recall Mode	None	C-Min		None	C-Min		None	None		None	None	
Walk Time (s)		7.0			7.0		7.0	7.0		7.0	7.0	
Flash Dont Walk (s)		11.0			11.0		11.0	11.0		11.0	11.0	
Pedestrian Calls (#/hr)		0			0		0	0		0	0	

Intersection Summary

Area Type: Other

Cycle Length: 140

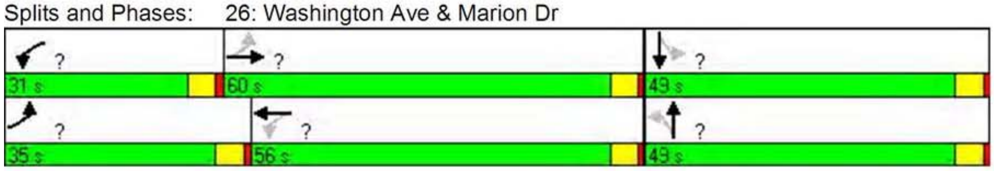
Actuated Cycle Length: 140

Offset: 127 (91%), Referenced to phase 2:EBTL and 6:WBTL, Start of Red

Natural Cycle: 55

Control Type: Actuated-Coordinated

Splits and Phases: 26: Washington Ave & Marion Dr

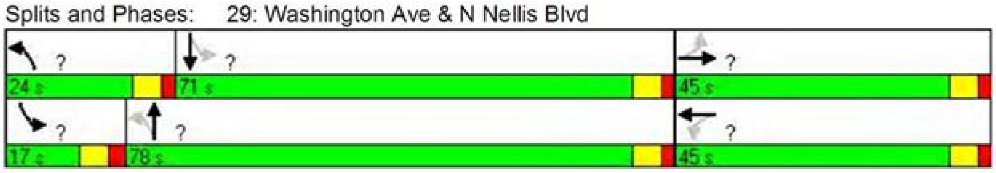


Lanes, Volumes, Timings
29: Washington Ave & N Nellis Blvd 2010-5-20

Lane Group	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Lane Configurations												
Ideal Flow (vphpl)	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900
Total Lost Time (s)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Leading Detector (ft)	49	49		49	49		49	49		49	49	
Trailing Detector (ft)	0	0		0	0		0	0		0	0	
Turning Speed (mph)	16		9	16		9	16		9	16		9
Right Turn on Red			Yes			Yes			Yes			Yes
Link Speed (mph)		35			35			45			31	
Link Distance (ft)		2643			1630			1986			1624	
Travel Time (s)		51.5			31.8			30.1			35.7	
Volume (vph)	84	260	196	116	190	80	216	1340	84	124	1904	79
Peak Hour Factor	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Turn Type	Perm			Perm			pm+pt			pm+pt		
Protected Phases		4			8		1	6		5	2	
Permitted Phases	4			8			6			2		
Detector Phases	4	4		8	8		1	6		5	2	
Minimum Initial (s)	4.0	4.0		4.0	4.0		4.0	4.0		4.0	4.0	
Minimum Split (s)	25.0	25.0		25.0	25.0		15.0	50.0		15.0	50.0	
Total Split (s)	45.0	45.0	0.0	45.0	45.0	0.0	24.0	78.0	0.0	17.0	71.0	0.0
Total Split (%)	32.1%	32.1%	0.0%	32.1%	32.1%	0.0%	17.1%	55.7%	0.0%	12.1%	50.7%	0.0%
Maximum Green (s)	39.0	39.0		39.0	39.0		18.0	72.0		10.5	65.0	
Yellow Time (s)	4.0	4.0		4.0	4.0		4.0	4.0		4.0	4.0	
All-Red Time (s)	2.0	2.0		2.0	2.0		2.0	2.0		2.5	2.0	
Lead/Lag							Lead	Lag		Lead	Lag	
Lead-Lag Optimize?												
Vehicle Extension (s)	3.0	3.0		3.0	3.0		3.0	3.0		3.0	3.0	
Recall Mode	None	None		None	None		None	C-Min		None	C-Min	
Walk Time (s)	7.0	7.0		7.0	7.0			7.0			7.0	
Flash Dont Walk (s)	11.0	11.0		11.0	11.0			11.0			11.0	
Pedestrian Calls (#/hr)	0	0		0	0			0			0	

Intersection Summary
Area Type: Other
Cycle Length: 140
Actuated Cycle Length: 140
Offset: 114 (81%), Referenced to phase 2:SBTL and 6:NBTL, Start of Red
Natural Cycle: 90
Control Type: Actuated-Coordinated

Splits and Phases: 29: Washington Ave & N Nellis Blvd



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