Adaptive Signal Control II

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ABSTRACT

This report is a comprehensive investigation of adaptive signal control. The literature review identifies the various control types and the typical benefits of adaptive control over other signal controls. Congestion, incidents and transit priority all are discussed and examined by modeling, first on a theoretical network, and then on four Salt Lake City area networks using field collected data. This modeling was possible through the University of Utah-built interface between the micro-simulation models CORSIM and VISSIM and the Split, Cycle and Offset Optimization Technique (SCOOT). It is important to note that the SCOOT system is not simulated by attempting to emulate the control algorithms. The micro-simulator sends detector information to the SCOOT system and SCOOT returns signal state, which then is incorporated by the micro-simulator. An actual SCOOT system provides control strategies to the micro-simulation environment. Therefore, if the micro-simulators are believed to be representative of the real-world environment, then the results of the analysis is how SCOOT performance and benefits will exist in the real-world.

The test network and corridor were operated at five congestions levels (0.7 v/c to 1.1 v/c) to identify the impact of congestion on benefits. An updated timing plan, optimized in Synchro, was compared to SCOOT controlled operations. The results show that SCOOT improves both network and corridor performance by reducing delay, queue length and travel time. However, SCOOT benefits on networks are higher than the benefits on a corridor. For example, SCOOT improves over optimized Synchro plans at 0.9 v/c, by up to 21 percent for a network. SCOOT improves by up to 13 percent for corridors. Improvements are small for both networks and corridors at and beyond saturation. This supports the field findings that while adaptive control can delay the onset of congestion and reduce recovery time, once saturation flow is reached congestion is inevitable.

The performance of SCOOT during incidents of 15, 30, and 45 minute durations for a range of traffic congestion levels shows that SCOOT reduced delay, queue length, and travel time, compared to an

optimized signal time plans. These benefits increase with increasing incident duration. For the range of congestion levels and incident durations examined, the benefits of SCOOT control during an incident range from 6.6 percent to 25.3 percent delay reduction. Results indicate that SCOOT reduces gridlock through metering and adapting to the measured demand requirements. This leads to quicker recovery from incidents and smaller delays, queues and travel times.

Transit patronage is based on reliable and timely service. Bus priority reduces travel times and improves reliability. However, with most buses running on the same traffic lanes as other traffic, giving transit priority can affect the surrounding traffic. Consequently, priority often is limited to small green time extensions or recall, and often only when buses are behind schedule. One of SCOOT's features is that it can provide bus priority while simultaneously reducing delay for all traffic. The SCOOT analysis along 400 South is compared to an actuated-coordinated optimal signal timing. Results show that SCOOT reduces non-bus vehicle delay by 16 percent or 4.4 seconds per person per intersection and bus delays by 27 percent or 9.2 seconds. Without bus priority, SCOOT reduced non-bus person-delay by 21 percent or 5.9 seconds per person and bus person-delay by 5 percent or 1.8 seconds per person. This means that SCOOT's bus priority facility can reduce transit delay with a minimal impact to other traffic.

The findings of this two-year study show that adaptive control has substantial benefits over a non-adaptive system. The results presented are compared to an updated and optimal fixed-times system - the best that an experienced traffic engineer can achieve, short of adaptive control. This means that the results reported are conservative because adaptive control performance is compared to an updated, optimized timing plan on the flows used in the modeling. In reality, the timing plans are based on a flow condition that varies day-to-day with weekly, monthly, and seasonal variations. The timing plans have been shown to age at 3-5 percent per year. Therefore, unless diligent effort is taken to ensure the timing plan is updated on a regular and frequent basis, the timing plan is rarely operating in the optimal condition. This should be intuitively understood as the timing plan is operating during a peak period which may be two to three hours in length. However, the optimal timing parameters of cycle, split and offsets are based on the peak hour with a peak hour factor considered. This means the timing plan that operates in the PM peak for three hours is derived from the worst 15-minute period. Even without daily variations and random changes in traffic flows, the PM peak plan only is optimal during that critical “design” 15-minute period. Inevitably, a fixed-time system is sub-optimal during the other two hours and 45 minutes. It is reasonable to assert, therefore, that adaptive control that continuously changes the cycle, split and offset based on the measured demand will always out-perform plan based control or even a coordinated vehicle actuated regime.

Consider a coordinated-actuated system during an incident. Queues on the main and side streets grow. Therefore, the actuated portion on the side street will experience high demand and therefore extend the side-street green time to the maximum phase length. This is counter to what should occur by providing more green time to the main street to “flush” the system. An adaptive control system measures the standing queue and combines “metering” and “flushing” to minimize blocking other intersections and better using the available capacity.

The drawbacks of adaptive control systems are that they are detector demanding. Adaptive control systems need real-time detector data. The decision to implement adaptive control has to be matched by a commitment to maintain the expanded detector system. Much like an actuated signal control, if detectors fail, then the benefits of adaptive control are eliminated as they revert to a fixed-time effectiveness.

This report concludes with a firm recommendation to deploy adaptive signal control. The research shows that adaptive control in SLC will bring immediate delay reduction and improved traffic control for many years to come.

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INTRODUCTION

Increasing traffic congestion is a constant source of frustration, time loss, and expense to users and managers of transportation systems. Cities, counties, and state transportation agencies are persistently searching for ways to mitigate urban traffic congestion, while minimizing costs and maintenance requirements. In urban areas, traffic signals are the limiting factors and common congestion points. Therefore, controlling traffic congestion relies on having an efficient and well-managed traffic signal control policy. Most areas use signal timing plans that correlate to specific times of day, such as morning and evening peak periods. Signal timings plans, however, are inflexible and do not change during each of these time-of-day intervals and are hence called "fixed-time" plans. Some more progressive systems use actuated-coordinated, which allows unused side street green time to be returned to the main street. This provides more capacity to the main street, but results in less efficient coordination, as the offsets do not adjust in real-time to the early platoon arrival at downstream intersections. Even these more progressive actuated systems do not adjust the cycle and therefore a single peak period is controlled by a constant cycle length. This implies that peak period traffic conditions remain relatively constant otherwise the "fixed-time" systems are less than optimal from cycle to cycle. All plan-based signal timings are known as "fixed-time" systems. Often this term is confused with "pre-timed," which is a rigid timing plan that does not incorporate actuation. Throughout this study fixed-time refers to a generic condition of either pre-timed or actuated-coordinated signal control, whichever provided the lower delay. Incidents on arterials raise another concern for congestion. Since fixed-time control does not respond to real-time traffic demand changes, they do adjust to reduced capacity.

Intersection Flow Variation

Fixed-time plans operate with the fundamental assumption that volumes are stable and one cycle length remains optimal throughout a design period. However, such volume stability rarely is the case, as traffic builds to a peak and then gradually subsides throughout the period. A study conducted at Fort

Union Boulevard and Union Park Avenue in Murray, Utah, examined the daily volume fluctuations and variability over a one-year period. In 2001, traffic volumes were measured in five-minute intervals between 4:00 to 6:00 p.m. on the third Thursday of every month. Figure 1.1 shows five-minute flow variation in February, May, August, and November to represent each quarter of 2001 and Figure 1.2 shows the monthly variations in total two-hour volumes at this intersection. The study shows that there are continuous fluctuations in traffic volume during a single peak period as well as throughout the year. Figure 1.2 shows that the five-minute volume fluctuation during the peak period can vary by 74 percent. This discrepancy in volume implies that traffic signals operating under fixed time control may operate optimally for a short interval when the existing volumes match the design volumes but during other intervals, the system operates sub-optimally. This is because fixed-time plans do not accommodate for these intra-peak period variations nor do they account for the annual fluctuations. Thus, updating these plans every few years becomes necessary [1].

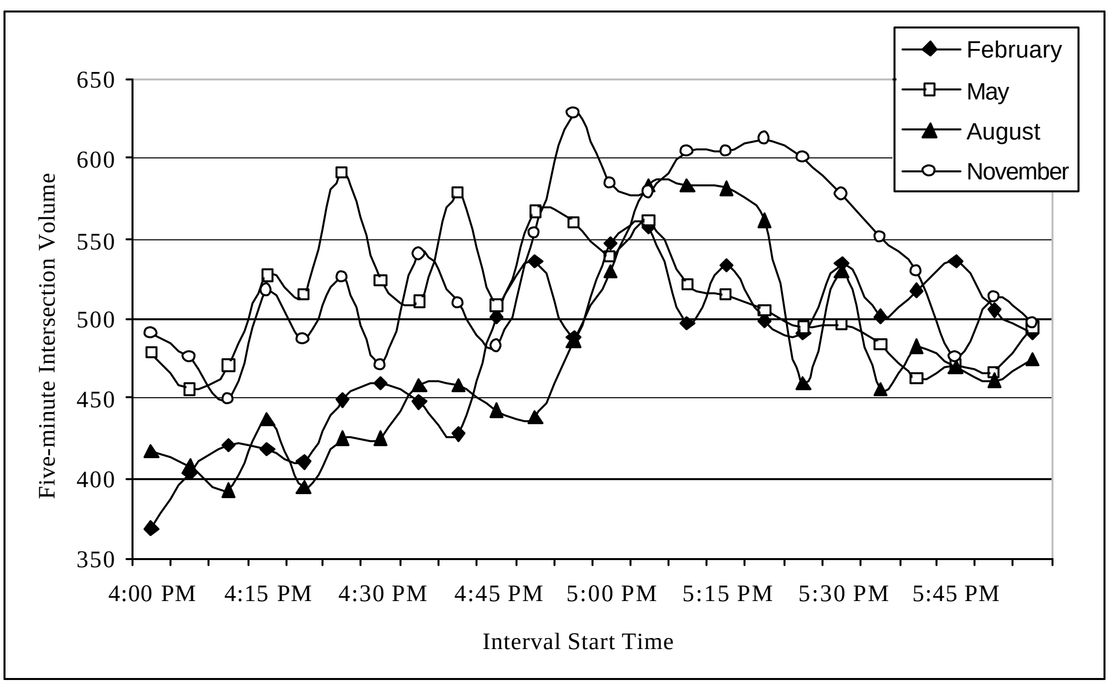


FIGURE 1.1: Daily flow variation in Murray, Utah in 2001

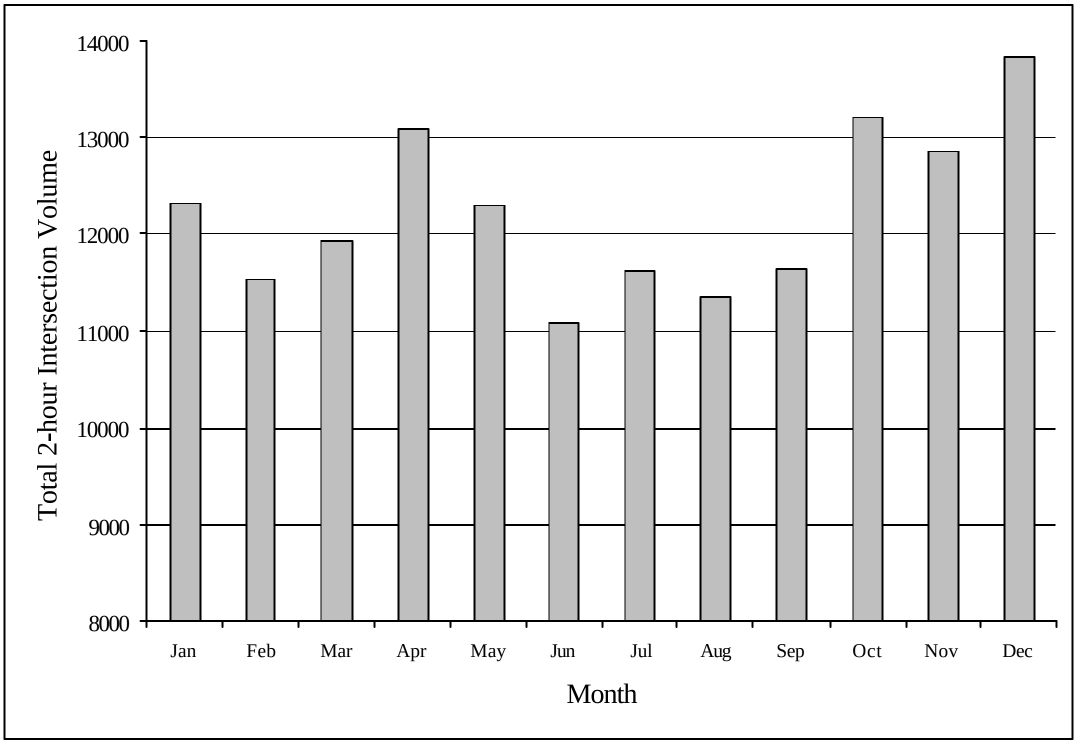


FIGURE 1.2: Yearly flow variation in Murray, Utah during year 2001

Arterial Incidents

Congestion is one of the most pressing traffic problems in urban areas. Incidents are expected to contribute to more than 70 percent of the total congestion at a cost of $48 billions by 2005[2]. Arterial incidents have a significant share in annual vehicle hours lost in congestion. According to the 2000 NHTSA statistics, 43.9 percent of the annual incidents that occur in United States are urban intersection related. During off-peak periods, when the traffic volumes are low, the lane section closures have little impact on the traffic flow. But when traffic flows are high, the lane section closure has a significant impact due to decreased arterial capacity. The reduced arterial capacity results in congestion. When the intersections are closely spaced, queues may spill into the upstream intersections affecting the traffic flow at the upstream intersections. Long queues also may lead to gridlock formation that takes longer time to dissipate. In general, incident congestion results in long queues, environmental pollution, longer travel times and lower throughput. To minimize the effects of congestion during incidents, several traffic control strategies can be used. The traffic diversion strategies attempt to provide knowledge of traffic conditions to drivers so they can make alternate route choice. Communication through in-vehicle devices or changeable message signs is required to give the drivers' incident and routing information ([3] and [4]). Traffic metering is an automated strategy that restricts the traffic flow into the incident affected area there by reducing the impact of incident congestion. Though this strategy is effective in alleviating the incident congestion, it causes congestion on other links in the network. Signal modification is an effective strategy for handling incident congestion. It is best applied when the demand does not exceed the total network reduced capacity after an incident occurs. Signal modification strategy gives significant benefits in delay minimization and queue length reduction [1]. Examples of signal modification strategies are longer or shorter cycle time, phase changes to reflect current demand, changes in the green splits and offsets to maintain equal queues for conflicting movements, and reverse progression.

Research Purpose

Adaptive Traffic Control Systems (ATCSs) belong to the latest generation of signalized intersection control [2]. ATCSs instantaneously detect vehicular traffic volume, compute optimal signal timings based on this detected volume and simultaneously implement them. Reacting to these volume variations results in reduced delay, shorter queues and decreased travel times [5]. While there are many ATCSs used in the United States of America (USA) and worldwide, the Split, Cycle and Offset Optimization Technique (SCOOT) [6] has been well established since its inception in 1981, with more than 170 installations world-wide. SCOOT improves network performance by adjusting signal timings in real-time by responding to measured traffic flows. This research uses the SCOOT-CORSIM Interface developed at the University of Utah [7] to connect SCOOT to the CORridor SIMulator (CORSIM) program. CORSIM is a microscopic simulation model developed by the Federal Highway Administration (FHWA). Since CORSIM allows traffic signals on the simulated networks to be controlled either by fixed-time plans or SCOOT, comparison of the two control regimes is possible. The research develops performance trends of SCOOT performance relative to the fixed-time control using theoretical networks to develop general relationships. Four Salt Lake area networks then are modeled to compare results on real-world networks. As one of the tasks, a bus priority evaluation of the adaptive control algorithms required completing a new interface. Since CORSIM cannot model transit, VISSIM, a microscopic simulation is used to model transit. The new interface between SCOOT and VISSIM operates similar to the existing CORSIM-SCOOT interface providing detector data from the micro-simulator to SCOOT and SCOOT provides signal timing information back to the micro-simulator. This new interface allows the SCOOT bus priority algorithms to be assessed in the VISSIM environment. The study results identify the benefits of adaptive control over fixed-time control during normal operations, incident conditions and with transit priority.

LITERATURE REVIEW

In the FHWA sponsored Urban Traffic Control System research project, signalized intersection control is classified into three generations [2]. The first generation systems of signal control used pre-stored signal timing plans that were calculated based on historical data. The second generation systems implemented signal timings that were calculated every five minutes based on surveillance data. However, to avoid large changes, these systems were restricted from changing timings in two consecutive five-minute periods. The third generation systems were similar to the second generation systems except that timings were allowed to change every 3-5 minutes. The literature review is subdivided into four sections: Operation and philosophies of various ACTS, SCATS and incidents, SCOOT and incidents, and incidents characteristics.

Adaptive Traffic Control Systems

ATCSs are third generation signal systems that make constant changes in signal timings based on measured flow. Reacting to these flow variations results in reduced delay, shorter queues and decreased travel times [5].

Several ATCSs have been developed and deployed around the world. ATCSs, such as SCOOT [6], Sydney Coordinated Adaptive Traffic System (SCATS) [8], Los Angeles Adaptive Traffic Control System (LA-ATCS) [9], MOTION [10], Microprocessor Optimized Vehicle Actuation [11], Prodyn [12] and UTOPIA [13] have been implemented in the field. Optimized Policies for Adaptive Control (OPAC), and Real-time Hierarchical Optimized Distributed and Effective System (RHODES) [14] have test installations, which show promise, while systems such as Control of Networks by Optimization of Switchovers [15] have only undergone preliminary testing in simulation but have not yet been deployed for testing. Figure 2.1 and Table 2.1 respectively show the number and installation locations, and the operational philosophies of the five systems, namely, SCOOT, SCATS, OPAC, RHODES, and LA-ATCS that are used in North America. Operation and philosophies of various ACTS are described below and summarized in Table 2.1.

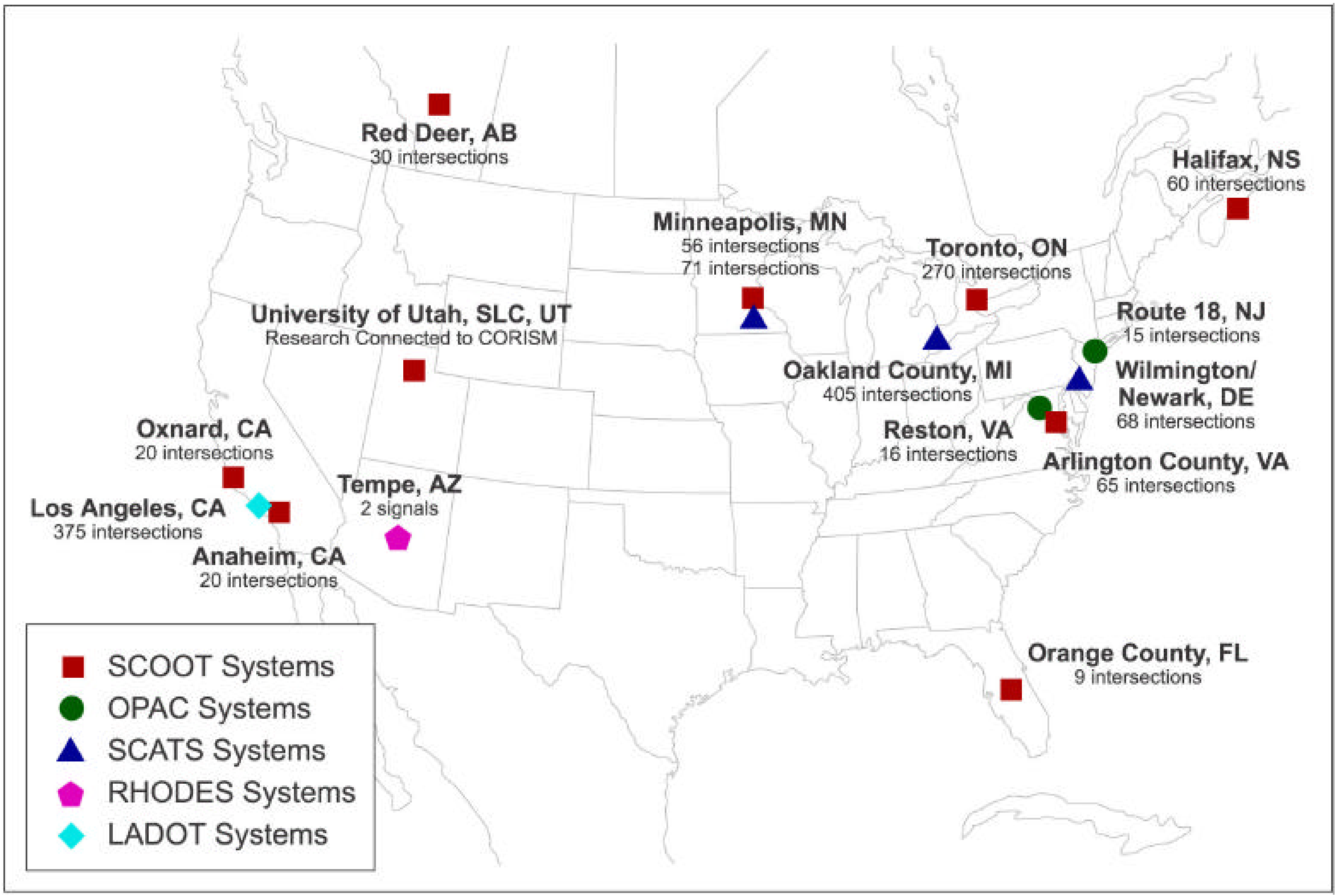


FIGURE 2.1: Adaptive Traffic Control System Installations in North America

TABLE 2.1: Summary of Adaptive Traffic Control Systems Literature Review

SYSTEM (Origin)	**Installations**	**Type of Installation**	**Processing Location**	**Central Computer**	**Field Controllers**	**Sensor Locations**
SCOOT (United Kingom)	More than 170 installations worldwide (4-600 intersections)	Field installation, Simulation	Central	DEC Alpha	NEMA, 170, 2070, TCT and TR0141	Upstream end of controlled link
RHODES (United States)	Three installations (Tempe, Arizona; Tucson, Arizona and Seattle, Washington)	Test deployment	Distributed	Not required	2070 with VME coprocessor	Upstream end of controlled link and stop-line
SCATS (Australia)	More than 50 installations worldwide (Australia, New Zealand, United States, China, Ireland, Singapore, Hong Kong and Tehran)	Field installation	Central for overall network control Distributed for local control of green phase	IBM PC with Windows ® NT™	2070/2070N 170 NEMA-Delta 3N In Australia, microprocessor based Philips and AWA models	Immediately in advance of stop-line Minor intersections require side street sensors only
OPAC (United States)	Two installations (Reston Parkway, Virginia and New Jersey)	Test deployment	Distributed, except for central control of cycle length	IBM PC with Windows ® NT™	2070 with VME coprocessor, 170 with 68360 processor, LMD 9200	Upstream about 8 to 12s from stop line or upstream of worst queue of all through phases
LA-ATCS (United States)	One installation (City of Los Angeles)	Field installation	Central	IBM PC	2070(new model) or 170	200 to 300 feet upstream of the stop-line

SCOOT

The Transport Research Lab in UK developed SCOOT [6]. The principal publication of SCOOT describes its philosophy and some preliminary field tests. SCOOT continuously measures traffic volumes on all approaches to intersections in the network and changes the signal timings to minimize a Performance Index (PI). This PI is a composite measure of delay, queue length and stops in the network. These changes in signal timings are made such that they are small enough to avoid major disruptions in traffic flow, but are frequent enough to allow rapid response to changing traffic conditions.

SCOOT, similar to the TRAffic Network StudY Tool (TRANSYT) [16] is a model based system that enables it to generate a Cyclic Flow Profile (CFP) based on the actual field demand. The fundamental unit of demand in SCOOT is a Link Profile Unit, which is a hybrid measure of the flow and occupancy data received from the detectors. Based on the generated CFP, SCOOT then projects platoon movement and dispersion at the downstream intersection. This helps it to model queue formation and queue discharge.

SCOOT is installed on a central computer and houses three optimizers: one for cycle time, one for green splits, and one for offsets. The cycle time optimizer computes an optimum cycle length for the critical intersection in the network. The split optimizer then assigns green splits for each intersection based on this cycle length and the offset optimizer calculates offsets. These parameters are recalculated and implemented every second and changes are made if required.

As accurate prediction and discharge of queues is pivotal to SCOOT's performance, validation of the field parameters, such as link journey time, maximum queue clear time and queue discharge rate is of utmost importance. Several agencies have carried out SCOOT evaluations comparing its performance to previously existing signal control strategies. Benefits realized from SCOOT depend on the prior control strategy and how well it had been optimized. The results of these evaluations showing percent benefits from SCOOT in delay and travel time are tabulate in Table 2.2.

TABLE 2.2: SCOOT Field Evaluation Results

Location of SCOOT Installation	Previous Control Method	Year	% Benefit over previous control method	
			Delay	Travel Time
São Paulo, Brazil (ver. 2.4)	Fixed-time (TRANSYT)	1997	0 – 40	-
São Paulo, Brazil (ver. 3.1)	Fixed-time (TRANSYT)	1997	0 – 53	-
Nijmegen, The Netherlands (ver. 2.4)	Fixed-time	1997	25	11
Toronto, Canada (ver. 2.4)	Fixed-time	1993	17	8
Beijing, China (ver. 2.3)	Fixed-time (Uncoordinated)	1989	15 - 41	2 - 16
Worcester, UK (ver. N/A)	Fixed-time (TRANSYT)	1986	3 - 11	7 - 18
Worcester, UK (ver. N/A)	Isolated Vehicle Actuation	1986	7 - 18	15 - 32
London, UK (ver. N/A)	Fixed-time	1985	19	6 - 8
Southampton, UK (ver. N/A)	Fixed-time	1985	39 - 48	18 - 26
Coventry, UK - Foleshill Road (ver. N/A)	Fixed-time (TRANSYT)	1981	22 - 33	4 - 8
Coventry, UK - Spon End (ver. N/A)	Fixed-time (TRANSYT)	1981	0 - 8	0 - 3

The latest published evaluation was the one performed by ‘Companhia de Engenharia de Trafego’, the traffic engineering company responsible for managing São Paulo’s traffic in Brazil [17]. The evaluation done in Nijmegen, The Netherlands compared SCOOT to fixed-time plans [18]. Before and after studies in Toronto, Canada, also compared SCOOT’s performance to coordinated fixed-time plans [19]. Benefits in Beijing, China, were higher than the most of the others as SCOOT was compared to uncoordinated fixed-time control [20]. SCOOT benefits were higher when compared to isolated vehicle actuation than coordinated fixed-time plans in Worcester, UK[21]. Evaluations in London [22], Southampton [23] and Coventry in UK also showed significant benefits from SCOOT back in the early 1980s. It should be noted however, that most of these results were not reported to be significant at 95 percent confidence level. Evaluations also were done in Santiago, Chile, [24] but were not expressed as percent benefit and hence were not comparable to the other results.

SCATS

SCATS originally was developed for the New South Wales Roads and Traffic Authority for application in Sydney and other Australian cities. Currently it has been installed in more than 50 cities worldwide. Similar to SCOOT, SCATS adjusts cycle time, splits and offsets in response to real-time traffic demand to minimize overall stops and delay. However, unlike SCOOT, it is not model based but has a library of plans that it selects from and therefore relies extensively on available traffic data. It can loosely be described as a feedback control system [8].

SCATS has a hierarchical control architecture consisting of two levels, strategic and tactical [8]. At the strategic level, a “subsystem” or a network of up to 10 intersections, is controlled by a regional computer to coordinate signal timings. These subsystems can link together to form a larger “system” operating on a common cycle time. At the tactical level, optimization occurs at the intersection level within the constraints imposed by the regional computer’s strategic control. Tactical control allows early termination of green phases when the demand is less than average and for phases to be omitted entirely when there is no demand. All the extra green time is added to the main phase or can be used by subsequent phases.

SCATS supports four modes of operations. The first or “normal mode” provides integrated traffic responsive operation. In the second or “fall-back mode,” time-of-day plans are implemented when computer or communication failure occurs. In the third mode or “isolated control mode,” there only is local vehicle actuation with isolated control, while the fourth mode, the normal signal display shows flashing yellow or flashing red on all approaches.

OPAC

Parsons Brinkerhoff Farradyne Inc., and the University of Massachusetts at Lowell jointly developed OPAC [25]. For optimization, the network is divided into sub-networks, which are considered independently. OPAC transitions between two models: one for congested networks and the other for uncongested networks.

In the uncongested model, the signal timings are determined one of two ways: Fixed-time plans are obtained off-line, or a "virtual cycle" is calculated dynamically. The level of local to network control can be configured by the user. The local signal timings are based on detected data (15 seconds) and predicted data (60 seconds). These are implemented for a time-step (roll period) of 2-5 seconds. In the congested model, OPAC considers the saturation flows and maximizes the number of vehicles that can pass through an intersection. It also considers the critical links as those on the verge of spillback. Except for the computation of cycle length, OPAC is not controlled by a central computer. Hence, it can run autonomously if communications to the central server fail. Unpublished literature also shows that OPAC can incorporate bus and light-rail transit priority, as well as emergency vehicle pre-emption. These test however, have only been done in a simulated environment.

RHODES

RHODES responds to the natural stochastic behavior of traffic, which refers to spatial and temporal variations and tries to optimize a given performance measure by setting timing plans in terms of phase durations for any given phase sequence [25].

The RHODES architecture has three levels of hierarchy. At the highest level the "dynamic network loading model" takes into account the slow-varying characteristics of traffic. The middle level is the "network flow control model," which allocates the green time based on the different demand patterns. The lowest level of the hierarchy is the "intersection control model," which determines the required phase change patterns.

Each level of hierarchy mentioned above has two components: the estimation/prediction component and the control component. Though these components already have been developed for the middle and the lowest level of the hierarchy, the network level algorithms still are under development.

The PREDICT algorithm [26] predicts flow at intersection level and the Controlled Optimization of Phases algorithm [27] does the controlling to adjust splits. At the network flow level, the APRES-NET model [28] predicts the platoon arrivals while the REALBAND algorithm [29] performs the optimization calculations.

RHODES also incorporates bus priority using the BUSBAND algorithm [30] provided that the location of the buses and the passenger counts for each bus are known. RHODES also has been linked to the CORSIM Simulation Program and hence can be tested in simulation.

LA-ATCS

LA-ATCS is a personal computer-based traffic signal control program [11]. It has three modes of operation. These are adaptive, time-of-day and operator control. LA-ATCS controls a group of intersections, each known as a section. In the adaptive mode, it operates on a common section cycle time determined on the basis of current flow conditions. Splits are determined based on the traffic volumes at each intersection and offsets are optimized to minimize stops. In the time-of-day mode, it operates on fixed time plans as determined by the engineer. The operator control mode is useful to handle traffic during special events and incidents.

All intersections in one section operate in a coordinated manner. The common cycle length of a section is computed based on the flow at the intersection having the highest level of traffic. This intersection is selected automatically by the system and changes as the traffic flow varies. The minimum and maximum cycle lengths are determined by the engineer and can be different for each intersection. Splits then are determined for each intersection based on the traffic flow at each approach of that intersection. After the splits are determined, offset optimization is done in the section so as to achieve the best coordination. Any of the three aspects of the system can be disabled for selected links in a section.

SCATS and Incidents

One of the features of an adaptive signal control is the ability to detect and respond to congestion. However, this feature gets negated when the queue from one intersection completely fills the link and blocks the upstream intersection. Since SCATS measures the degree of saturation based on detector occupancy, rather than the actual volume departing from the intersection, the detector cannot differentiate between a high flow rate (high occupancy and large number of vehicles departing from the intersection) and intersection blockage (high occupancy but low number of vehicles departing from the intersection). Hence, SCATS cannot respond to congestion when the queue from one intersection completely fills the link and blocks the upstream intersection.

In a SCATS installed network, traffic operators primarily activate response to incidents. When the detectors are covered by traffic for certain period, an alarm is signaled to the traffic operator who sets the traffic control [31]. SCATS has a tactical logic that also can respond to incident-related congestion. The logic is the same as the normal recurrent traffic operation. At each intersection the tactical control strategies include:

- Signal split selection from a library according to degree of saturation
- Green time early cut-off due to inefficient use of green time
- Phase skip if no demand is placed in the previous cycle.

At a “strategic” level of control, offset and cycle time are selected in response to the current traffic situation based on the plan selection process. However, the plans typically are not developed for incident situations. In principle, when an incident occurs on a link, there is a reduction in traffic at the downstream intersection. The reduction of the green time for that direction will be given to other phases by means of any of the four strategies. At an intersection upstream from the incident, if blockage exists and reduces the flow, the green split is reduced by the split plan change and the early cut-off. SCATS do not have logic to prevent intersection blockage.

Limited research has been done to evaluate the performance of adaptive signals during incidents. Dr. William C. Taylor and Sorawit Narupiti conducted research to find whether SCATS can detect incident congestion and examine how the system dealt with this congestion[32]. They reported that SCATS is not efficient in handling incidents. William C. Taylor and Ahmed S. Abdel-Rahim evaluated the performance of SCATS for on a roadway with 85 percent reduced capacity for durations of 5, 10, and 15 minutes [33]. The research to evaluate the performance of SCATS during incidents reveled that SCATS does not have a special inbuilt modules or logic to automatically respond to incidents.

SCOOT and Incidents

Comparison with fixed-time control showed that SCOOT reduced delay and travel time, thereby improving traffic network performance. Early evaluations in UK showed that SCOOT typically reduced delay by up to 33 percent and travel time up to 8 percent. The literature also indicated that validation of SCOOT during installation is extremely important. A non-validated SCOOT system in Nijmegen worsened system performance but when properly validated, it improved delay by 25 percent and travel time by 11 percent.

SCOOT identifies congestion using the detectors that are placed upstream of an intersection. As queues form along the whole length of the link, the occupancy of the detectors increases. SCOOT uses this data to identify exit blockage at an intersection and keeps its traffic model up to date accordingly. SCOOT has an inbuilt module called Integrated Incident Detection (INGRID) and Automatic SCOOT Traffic Information Database (ASTRID) to detect the incidents in the urban areas controlled by SCOOT.

ASTRID Philosophy

The ASTRID data is derived from a special format of output from SCOOT. The data is transferred from the SCOOT computer to the ASTRID in compressed form every minute. ASTRID operates online to enable the information on the current state of the network to be accessible for identifying incidents. Data displayed by ASTRID is either collected directly from SCOOT or calculated from stored information. The user can access both types of data. The following data items are collected directly from SCOOT messages.

- Flow: The flow of vehicles arriving at the stop line, as modeled by SCOOT.
- Delay: The total delay in vehicles per hour.
- Congestion: The percentage of four seconds intervals when a detector is occupied by traffic. This value is independent of the SCOOT model.

Other SCOOT data, such as degree of saturation on a link or stage lengths can also be collected. ASTRID also accepts data from non-SCOOT sources such as vehicle count detectors, or car park occupancy detectors. For all SCOOT detectors in the network, a daily profile of the expected flow and occupancy in each 15-minute time period is stored and automatically updated in the ASTRID database. Thus, ASTRID has all historical data required by INGRID to identify incidents.

INGRID Philosophy

The automatic incident detection (INGRID) is developed with the objective of detecting incidents automatically so the information can be provided to the road user.

Two algorithms are used in INGRID to detect incidents. One examines current traffic data for sudden changes in flow and occupancy. No reference data is required for this algorithm. The other algorithm uses historic reference data provided by the ASTRID database. The algorithms detect incidents by comparing the current traffic situation with that expected from the historic reference data in ASTRID. The functioning of INGRID has six basic principles: immediate incident detection, historical comparison of data, conformation of a detected incident, congestion detection, severity index of incident and incident reporting.

Immediate Incident Detection: This algorithm requires data on the flow and occupancy over consecutive loops to detect an incident in the road space between them. Incidents are indicated when there is significant decrease in flow and occupancy at the downstream detector.

Historical Comparison: There are three separate routines, which detect incidents by comparing current traffic situation with the ASTRID database. The “slow build up” method indicates an incident downstream of a detector when for three consecutive minutes there is an increase in current occupancy and a decrease in current flow outside the confidence interval of the reference data. A variation on the "slow build up" method indicates an incident when conditions are satisfied for the data for one signal cycle. The "Regression" method calculates the gradient of regression for successive one-minute occupancy counts and is compared with the reference data. An incident is indicated when two gradients diverge significantly.

Conformation of a detected incident: conformation of an incident is achieved in space and time. An incident is conformed if occupancy increases and flows decrease on the upstream detectors and flow and occupancy decrease on the downstream detectors for successive time intervals.

Congestion detection: This algorithm detects general levels of traffic congestion. It is used as an indicator of congestion over an area, rather than for individual detectors.

Severity Index: Once the incident is detected, the severity index considers the area affected by the congestion due to incident and the additional delay to vehicles traveling through the affected area. This can be mapped to give a visual representation to the transportation managers.

Incident Reporting: When an incident is detected, INGRID provides a message on the Romance Central Processor. The INGIRD incident reporting format is shown in Figure 2.2. INGRID is just an incident detection algorithm that identifies and reports the occurrence of incidents.

Time	Date	Detector	Region	Duration
08:18:23	20051995	N07111A1	REG_SW	08 Minutes
	Confidant of a **severe** incident			
List of affected detectors:		Affected up:		N07121J1
		Affected Down:		N07123B1

FIGURE 2.2: Incident reporting by INGRID

Further development is needed to provide incident information directly to a traffic control system so automatic signal action could be taken. For this, INGRID has to determine the effects of an incident on the capacity of the intersections immediately upstream and downstream of the incident. Once the effect of incidents is determined, the traffic control system can take appropriate action. Some of the UTC strategies, which could be used in response to an incident, include allowing larger changes in signal timings being made than under normal SCOOT control or altering the saturation occupancy on affected links [35].

As stated in section 2.1, limited research has been done in evaluating the performance of ATCSs during incidents. The benefits of SCOOT over fixed time based signal control during incidents are evaluated at Coventry, United Kingdom. The evaluation showed that there is a 21 percent reduction in delay at the network level and 28 percent reduction in delay per vehicle on the diverted route [35]. The evaluation is done under very specific conditions like under-saturated traffic condition, a single incident scenario of arterial closure, and incident duration of three hours.

Incident Characteristics

Incidents are complex scenarios that cause congestion. The decrease in roadway capacity leads to lower traffic flow through the arterial, leading to congestion. Once the incident site is cleared and the roadway capacity is restored, it takes additional time for the traffic flow to recover. The dynamics of an incident scenario are illustrated in Figure 2.3.

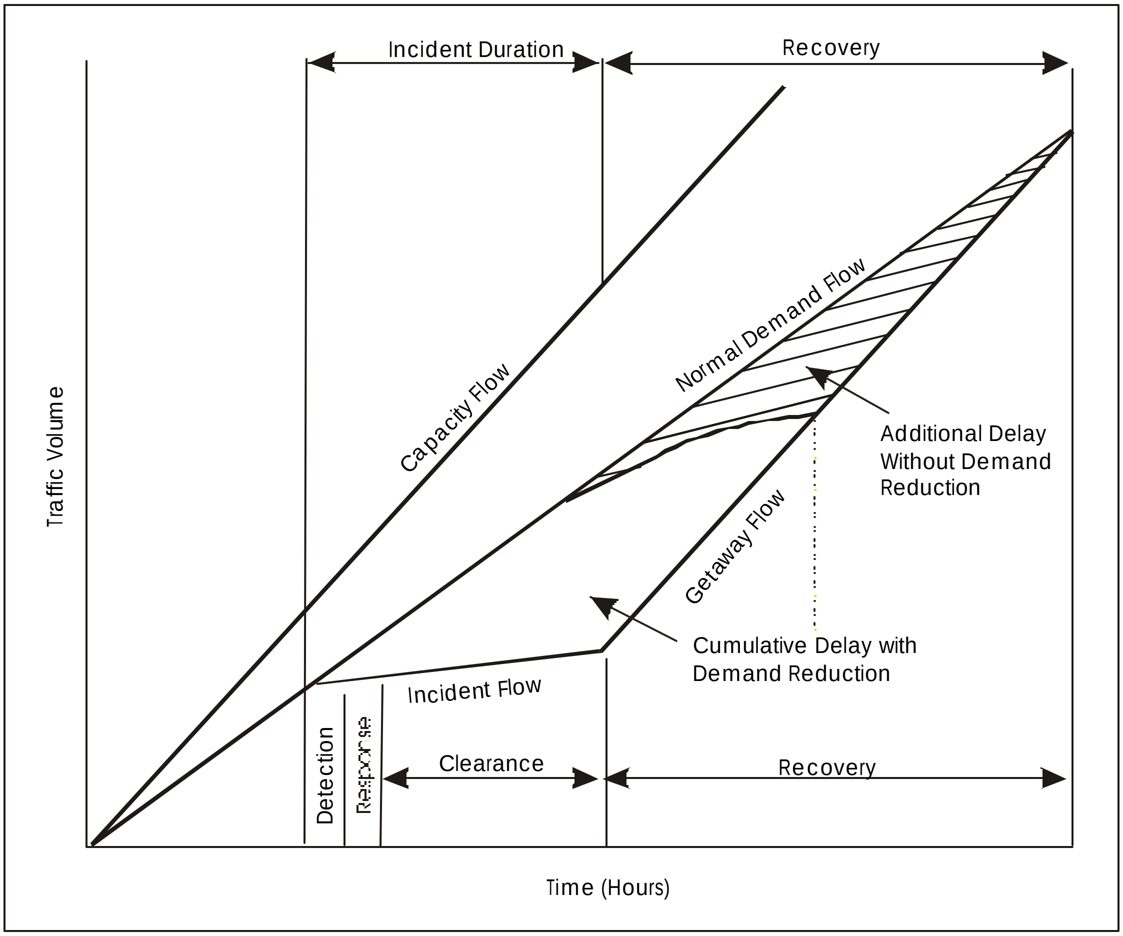


FIGURE 2.3: Schematic of traffic flow during an incident

In the Figure 2.3, the area that lies between the normal demand flow, getaway flow, and the lower incident flow represents the extra delay incurred by motorists, due to the incident. The queue will continue to build until the incident is cleared and the traffic flow is restored. This research compares the slopes of getaway flow line during fixed-time and SCOOT control for various network traffic congestion levels. The slope getaway flow line represents the recovery from the incident. It is estimated that just 40 percent of the traffic congestion is due to inadequate roadway capacity, whereas, 60 percent of traffic congestion is due to incidents. Hence incidents have a significant share in annual traffic congestion. Therefore, savings in the costs of building new roads and the widening of existing roads can be realized with incident management, which seeks to manage the flow with the existing road capacity. The objectives of congestion control during incidents are location dependent [6]. Among the most popularly used optimization objectives of incident management are overall travel time reduction, maximization of throughput, and minimization of queues [36]. Incidents are a complex scenario that is defined by a number of variables [21].

- Incident scenario: This is defined by the number of lanes blocked.
- Incident duration: This is defined by the duration for which the lanes were blocked.
- Incident location: This is defined by the location of the incident. The impacts of mid-block incident are different from the impacts of intersection incidents.
- Road length blockage: The length of road blocked is also an important parameter in defining the incident.

National Transportation Statistics report that 80 percent of the incidents last for 30 minutes with a standard deviation of 15 minutes [37]. It is reported that 40 percent of the incidents block one lane, or occasionally two lanes [38]. It is difficult to quantify the cost of an incident. The congestion due to an incident is dependent on the time of day, layout and control of the incident, and existing traffic demand flow level [39]. If the traffic flow levels are high, an incident can cause a gridlock in the network thereby all the traffic flow stops. It is even more difficult to put a price on such disruptions [40].

FIXED-TIME SIGNAL CONTROL

As this research evaluates the effectiveness of SCOOT by comparing its performance to fixed-time control, different types of fixed-time (FT) control strategies and various optimization software are examined here.

Types of Fixed-time Signal Control

Fixed-time signal control can be classified as either pre-timed control or actuated control. Further, each of these strategies can be applied either to an isolated intersection or to a signal system.

Pre-timed control has repetitive signal cycle and split timings in case of isolated intersections. This means that the cycle length and duration of splits remains constant. The phase sequence for each cycle also remains the same. When in a signal system, all intersections operate on a single cycle length and constant offsets. On the other hand, actuated control provides variable length of splits for phases that are equipped with detectors. Actuation at isolated intersections adjusts green interval lengths and phase sequences continuously, depending on detected demand. However, offsets remain constant in case of actuated control. Based on the extent of detection (or actuation), actuated control is further categorized as semi-actuated of fully actuated.

Semi-actuated control: Semi-actuated control is deployed at intersections where a major road intersects a low volume road. Traffic movements can be differentiated as major or minor based on the volume of traffic they carry. Semi-actuated control also is classified as coordinated or un-coordinated. In semi-actuated coordinated control, the major movement always is coordinated and detection is along the minor movement. This means that the major movement always is green for a certain fixed time during a signal cycle thereby providing progression along a corridor. For the remaining duration of the cycle, the side street receives green time only if a vehicle is detected. If no vehicle is detected along the minor movement, the additional green time is given to the major movement.

In semi-actuated un-coordinated control, detection is similar to semi-actuated coordinated control but the major movement is not under progression. The major movement remains green until a vehicle is detected along the minor movement, in which case the minor movement receives green. The minor movement then remains green until traffic is cleared or it reaches its maximum (whichever occurs earlier) and then green is transferred back to the major movement.

The main difference between these strategies is that in coordinated actuation, a bandwidth of progression always is maintained by keeping the major movement green for a fixed interval of time during the cycle, while in un-coordinated actuation, the green along the major street can start and end during any time in the cycle. Coordinated semi-actuation is used for corridors while un-coordinated semi-actuation is used for isolated intersections.

Fully actuated control: Fully actuated signals are found at intersections that exhibit large fluctuations of traffic volumes from all of the approaches during the day. Detectors are placed on all approaches. There is a set minimum and maximum green time for each phase. The moving traffic will receive green time unless the opposing vehicles are stopped at the intersection. The minimum green time often is set equal to the time required for a pedestrian to safely cross the intersection. Pre-timed and actuated controls both have their advantages and disadvantages [41]. Good coordination can be achieved in pre-timed control because of consistent cycle lengths and splits. Closely spaced intersections and intersections with high pedestrian volumes perform better with pre-timed control. Due to absence of detectors, pre-timed control is cheaper to install and maintain, and is free from detector related faults. Actuated control on the other hand give higher efficiency when volume variations are high or when signal control is needed for brief periods. They increase safety by reducing rear-end collisions. Detection allows ability to have demand dependent phases and requires less future engineering to ensure best fit between demand and signal timing.

To decide the type of fixed-time control to be used as a baseline condition, a test corridor for four intersections and a test network of 16 intersections were modeled. Schematic layout of the network is shown in Figure 3.1 with the corridor demarcated with a gray band.

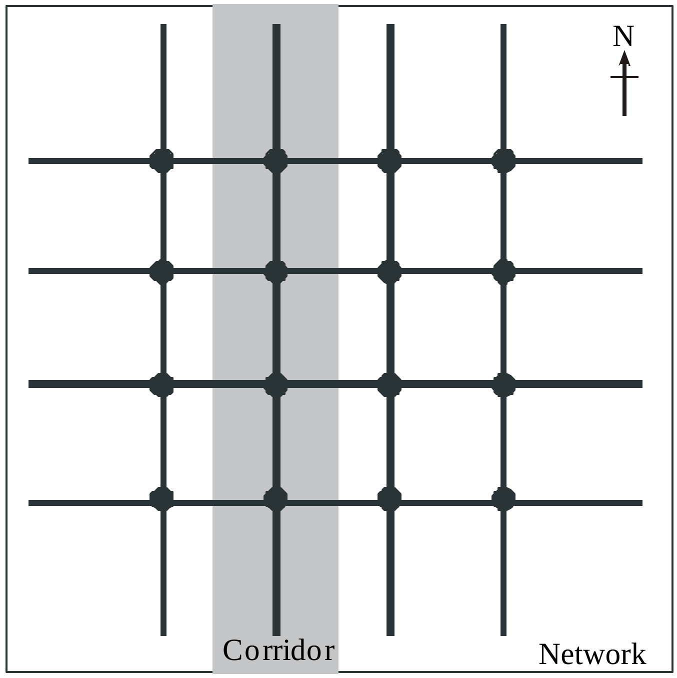


FIGURE 3.1: Schematic layout of Test Network

After flows and geometry for the network and corridor were coded for this research, the type of fixed-time control to be used as the baseline condition had to be decided. As geometry of the corridor and network was similar at all approaches of all the intersections, and the network volume represented peak-hour traffic, it was anticipated that pre-timed control would perform similar to actuated control. Therefore, the corridor and network were evaluated for all fixed-time control strategies at volume-capacity ratios (v/c) ranging form 0.7 to 1.1. Results shown in Table 3.1 for corridors and Table 3.2 for networks indicated that, actuated un-coordinated control and fully actuated control gave similar delays while pre-timed control and actuated coordinated control gave similar delays. Results also showed that pre-timed or actuated coordinated control gave lower delays than actuated un-coordinated or fully actuated control.

TABLE 3.1: Overall corridor delay (veh-hrs) for fixed-time control strategies

V/C	**Pretimed Control**	**Actuated Control**		
		Actuated un-coordinated	**Actuated coordinated**	**Fully actuated**
0.7	67	75	67	75
0.8	101	116	101	116
0.9	142	164	143	164
1.0	241	258	241	258
1.1	415	443	415	443

TABLE 3.2: Overall network delay (veh-hrs) for fixed-time control strategies

V/C	**Pretimed Control**	**Actuated Control**		
		Actuated un-coordinated	**Actuated coordinated**	**Fully actuated**
0.7	174	248	175	246
0.8	267	339	265	338
0.9	397	513	399	509
1.0	653	827	643	827
1.1	1112	1374	1111	1374

As green times for all phases reached their maximum values during the peak period, an actuated-coordinated system performed just like a pre-timed system, and an actuated un-coordinated system performed just like a fully actuated system. Based on these results, pre-timed control is used in this research as a baseline to compare with SCOOT.

Signal Timing Optimization Software

Several signal timing optimization software, such as TRANSYT [16], Synchro [42], Passer [43], Signal Operations Analysis Package (SOAP) [44] and SIG/Cinema [45] are used in industry and academia. These programs vary in terms of their optimization scope and user interface. TRANSYT and Synchro perform intersection, corridor and network wide optimization, Passer optimizes corridors while SOAP and SIG/Cinema optimize isolated intersections only. TRANSYT is Disk Operating System (DOS) based and has a command line interface while Synchro, Passer, SOAP, and SIG/Cinema have a Microsoft® Windows™ based Graphical User Interface (GUI).

Synchro is widely accepted in USA and is preferred by the Utah Department of Transportation (UDOT), the sponsor of this research. The philosophy of Synchro is described below in detail. Trafficware Inc., a company based in Albany, Calif., developed Synchro. It is a software package for modeling and optimizing traffic signal timings, and is a Windows-based program with an interactive GUI. There are two levels of Synchro available in the market. Each has different features. The SynchroLight has a limit of 10 intersections while up to 300 intersections can be modeled in Synchro.

Synchro minimizes a PI to improve network performance. The PI is a composite of delay, number of stops and the number of vehicles affected by the queue. Once the network is built in Synchro by providing geometry, volume information, optimization is done. Different optimizers that work at different levels. At the intersection level, Synchro optimizes green splits and cycle lengths at each intersection considering it as an isolated intersection. The network, if required, then is fragmented into corridors, each knows as a zone. If such fragmentation is not desired, the network is left as a whole. Synchro then computes an optimal cycle length for each zone or the network. In the next, offsets and phase sequence are optimized. In this step, Synchro computes offsets to increase progression and optimizes for leading or lagging left turns. Once all the optimization is done, the signal timing plans can be viewed in the "Timing Window."

The analysis evaluated TRANSYT and Synchro and compared the performance of each model, relative to the other. The comparison identified that the Synchro modeling consistently produced lower

MOEs relative to the TRANSYT modeling. Therefore, the more conservative research approach is to compare SCOOT with the Synchro optimized FT plans.

CORSIM, SCOOT AND THE INTERFACE

After evaluating different fixed-time control strategies and the software programs available for signal-timing optimizations, the modeling tools primarily used in this research are described. This chapter explains the functioning of three programs: CORSIM, SCOOT and the SCOOT-CORSIM Interface. The traffic environment was simulated using CORSIM, SCOOT was the ATCS used, and the Interface enabled SCOOT to control CORSIM simulated networks.

The CORSIM Program

CORSIM is a module of the Traffic Software Integrated System (TSIS) tool suite [46]. KLD Associates developed TSIS for FHWA. Currently, TSIS is supported by ITT Industries, Inc. and is distributed by the Center for Microcomputers in Transportation at the University of Florida. CORSIM is a composite program of the Freeway Simulator (FRESIM) and the Network Simulator (NETSIM) [47]. FRESIM is used to simulate freeway traffic, while NETSIM is an urban traffic simulator. Classified as a microscopic simulation program, CORSIM models interactions of individual vehicles in a user-defined network using traffic flow algorithms. Vehicles are moved according to car-following logic in response to traffic control devices simulated at the intersections. Each vehicle has stochastic attributes such as vehicle length, driver aggressiveness, acceleration rate, minimum acceptable gap, and maximum free speed.

To simulate a traffic network, CORSIM executes an input file that contains data regarding the desired traffic environment. Characteristics of this traffic environment either change over time during a simulation or they change over space, but are constant during the length of one simulation run. Characteristics such as entering traffic volumes, intersection turning movements and signal timings can vary during a simulation run, while characteristics such as traffic geometry may be different for each intersection or approach but remain constant during one simulation run. After each simulation, CORSIM generates an output file that enables extraction of Measures of Effectiveness (MOEs) such as delay, travel time and queue lengths. These MOEs helped to evaluate effects of the applied control strategy on the traffic network.

A CORSIM input file is a text file in which input data is lumped into categories. Each such category is known as a “record type.” Characteristics such as simulation duration, network geometry, entering flows, intersection turning movements, and signal timings, each have their own record type. A CORSIM input file can be created by typing the file directly in a text editor as per the syntax in the CORSIM User Manual [48]. Writing the input text file however, is highly time consuming and not economical. Therefore, pre-processors such as Synchro, ITRAF and TRAFED, which have a GUI to create the network, and then export it in a CORSIM input file format can be used.

Similar to the input file, the output file generated by CORSIM following the simulation also is a long, cumbersome-to-read, text file. Extracting MOEs from such a text file consumes a lot of time and effort. Therefore, programs known as post-processors, which have a GUI, can be used to facilitate the extraction of MOEs from the CORSIM output file. ACCUSIM is an example of such a post-processor and was extensively used in this research to facilitate MOE extraction. Figure 4.1 shows a snapshot of an ACCUSIM screen. The Traffic Visualization Utility (TRAFVU) that is a part of the TSIS package was also used to see the animation of the simulation.

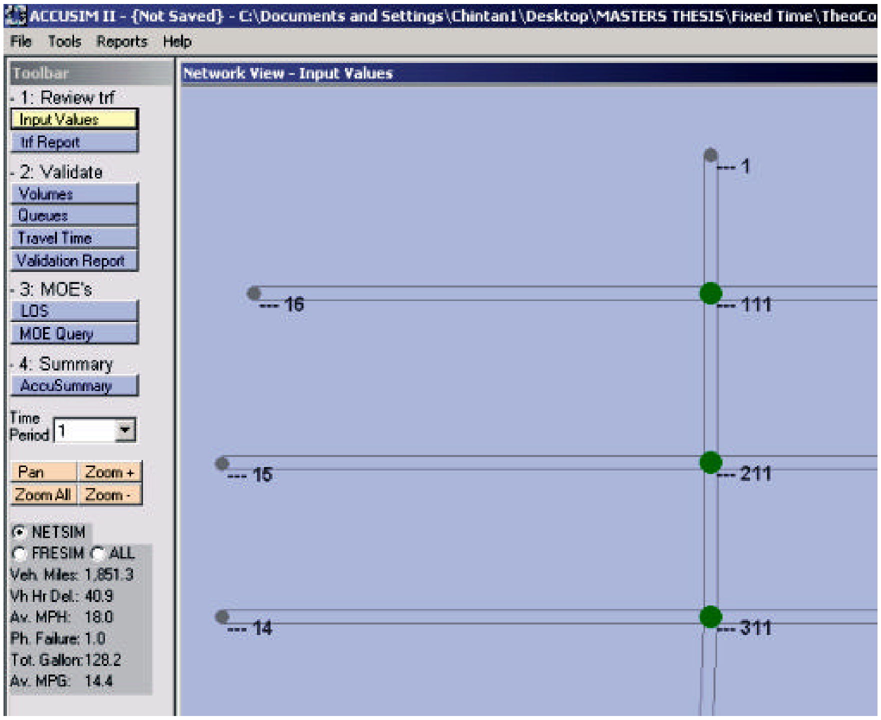


FIGURE 4.1: ACCUSIM Program Snapshot

Figure 4.2 is a snapshot of the TRAFVU program with view being zoomed at a single intersection. Viewing this animation helped model calibration and validation, which is explained in detail later.

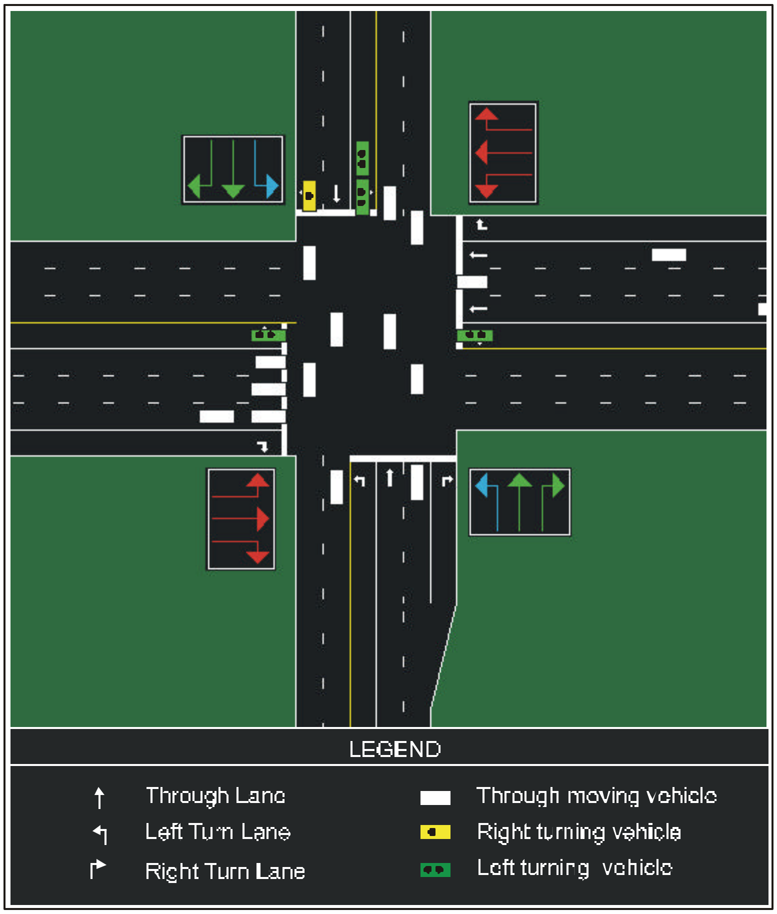


FIGURE 4.2: A TRAFVU Animation Snapshot

CORSIM does not have a record type for simulating incidents at user-defined incident locations on a network. Therefore, to simulate an incident in a CORSIM network, the arterial is split into three segments. One segment is at the upstream of incident. Second segment is the bottleneck. The third segment is downstream of the incident. The three segments are 200, 50 and 750 feet long. The lane closure is imposed on the second segment only for the duration of the incident. Figure 4.3 shows a modification made to the CORSIM network to simulate incidents.

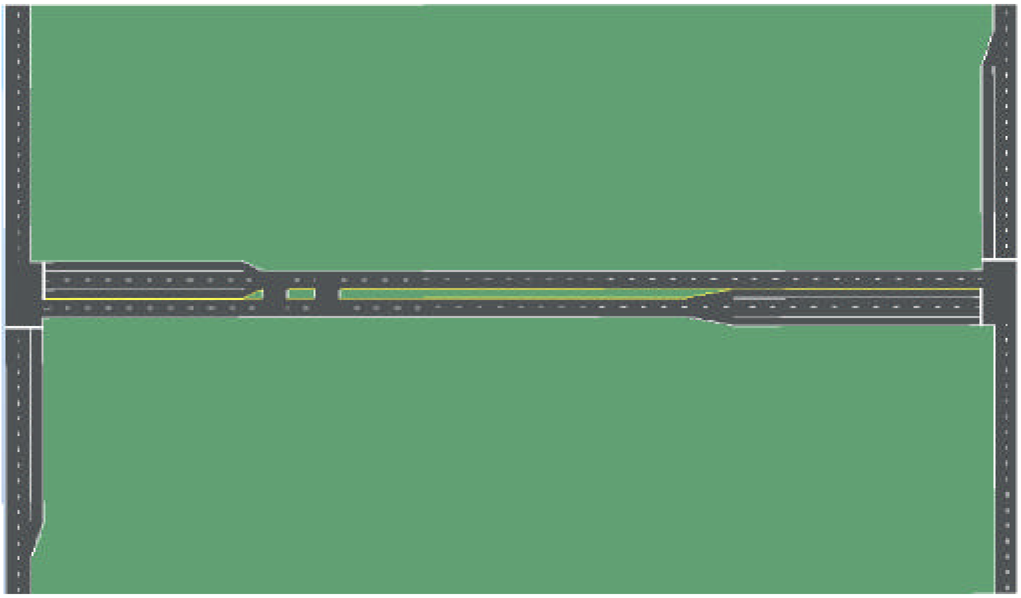


FIGURE 4.3: Incident on a CORSIM network

All the simulations have 30 minutes of priming period and two hours of volume varying simulation. Incidents of 15, 30, and 45 minutes durations are simulated starting and ending at different times during the simulation. Figure 4.4 shows the schematic diagram of the timing of the incidents.

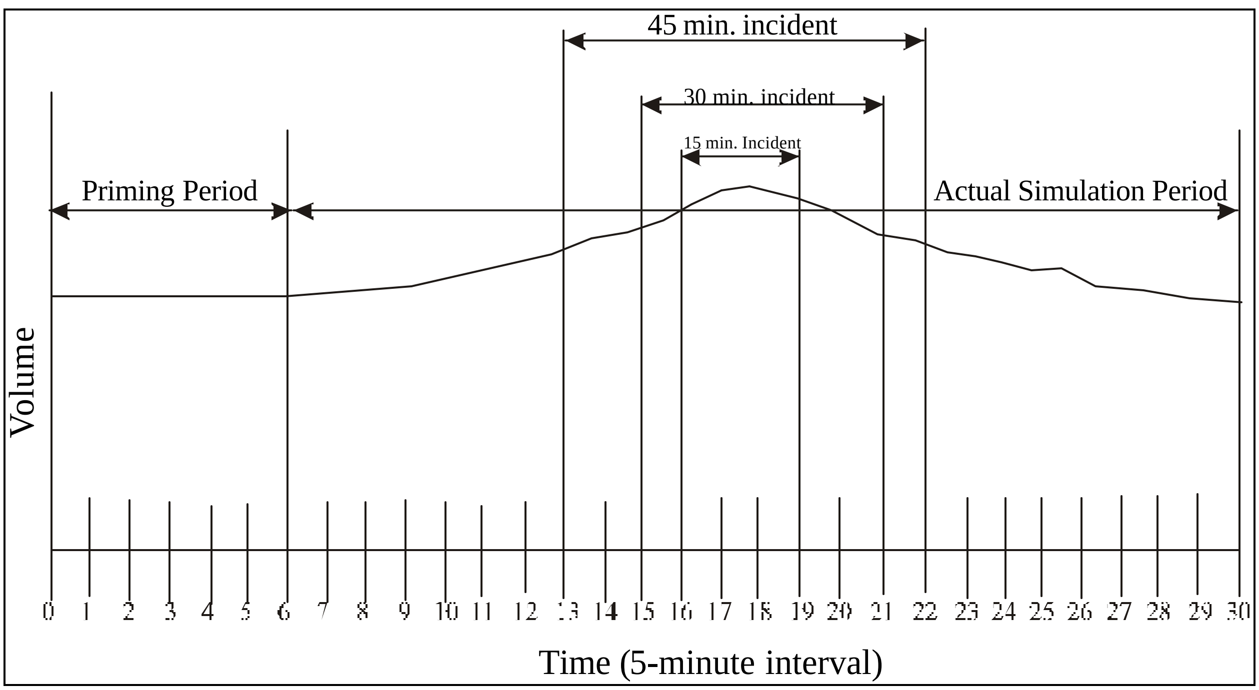


FIGURE 4.4: Timing of the incidents

The 15-minute incident is simulated starting at 1:20 hours and ending at 1:35 hours, from the beginning of the simulation. The 30-minute incident is simulated from 1:15 hours to 1:45 hours. A forty-five minute incident is simulated starting at 1:05 hours and ending at 1:50 hours. The incidents are simulated under FT and SCOOT control.

The SCOOT Program

The following discussion explains the SCOOT data base hierarchy and enlists enhancements in subsequent SCOOT versions. The database hierarchy represents the order in which SCOOT stores data. The hierarchy follows a macro-to-micro pattern with a SCOOT "area" at the top of the tree and a SCOOT "stage" or a SCOOT "detector" at its lowest end. These terms are explained below. Figure 4.5 illustrates the SCOOT database hierarchy.

- Area: A SCOOT Area represents the whole network under SCOOT control. An area is a collection of SCOOT regions.
- Region: A SCOOT Region comprises a group of nodes that operate under SCOOT at a common cycle length. Nodes in which coordination is desired are grouped together in a region.
- Node: A node is an intersection under SCOOT control.
- Link: A link is a path that carries traffic into or out of a node. Based on their location respective to a node, links are classified as entry links, normal links, exit links, or filter links.
- Detector: A detector is a magnetic loop or some other device that detects vehicle flow for a particular link.
- Stage: Commonly termed as "a phase" in USA, a stage represents a set of movements that are allowed the right-of-way for a particular interval during a signal cycle.

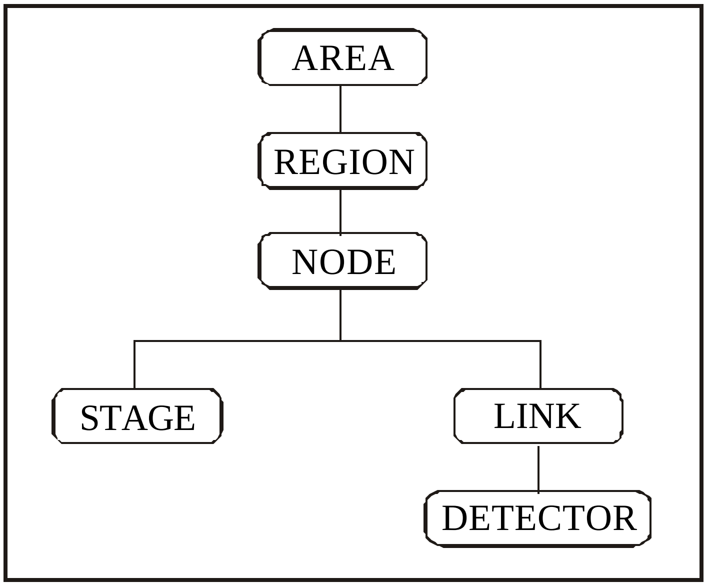


FIGURE 4.5: SCOOT Database Hierarchy

New ideas and suggestions from the users and developers of SCOOT have contributed to its development. Since its introduction in the early 1980s, major changes to SCOOT were seen in 1990 with the introduction of version 2.4 [40]. This version enabled SCOOT to predict saturation occupancy using the on-line saturation flow technique. The feedback facility was introduced, which helped SCOOT to model queues during unexpected changes such as priority calls and demand dependent stages. Gating, a feature that works on a similar principle as ramp-metering, was introduced. Gating helped SCOOT to hold traffic at upstream, less congested intersections, where storage was less critical. The facility to model bicycle lanes was also introduced in this version.

Version 3.0/3.1 was the next version of SCOOT [49, 50]. Bus priority using automatic vehicle detection was introduced in this version. Split and offset weighting also were introduced, which enabled a user to give higher priority to certain approaches. This version also allowed the user to set the maximum allowable saturation levels, which were previously fixed at 90 percent. The handling of faulty links also was introduced by which SCOOT switched to a default phase length in case all detectors on a link were detected faulty. The Automatic SCOOT TRaffic Information Database (ASTRID) also was introduced in this version [51]. ASTRID stored data from a variety of parameters given by SCOOT, which could then be used for trend evaluation and reporting.

Version 4.2 is the current version of SCOOT [41]. In this version, ASTRID data that was first used only for analysis is now available to the SCOOT optimizers. ASTRID data is used by SCOOT to influence its decisions based on historic trends or to compute timings if the detectors on a link become faulty. This version also facilitates the use of stop-line detection. Modeling of flared intersection approaches also is possible. New algorithms have been introduced to help SCOOT recover more effectively from priority calls. Enhancements in this version also allow SCOOT to model some links without any real detection.

The University of Utah has an “academic license” of SCOOT version 3.1. Though this license has all features available in the regular version 3.1, the academic version has two main limitations:

- Formation of a maximum of one SCOOT region: This means that only one SCOOT region can be defined in a network at a time. As all intersections in one SCOOT region operate at a common cycle length, SCOOT performs sub-optimally if there is a wide variation v/c ratios within a network.
- Maximum of 30 intersections under SCOOT control: This means an area bigger than 30 intersections cannot be under SCOOT control. Though the simulated network can have more than 30 intersections, only up to 30 intersections can be set under SCOOT control during one simulation run.

The SCOOT-CORSIM Interface

In a typical field installation, the SCOOT computer communicates directly with another computer. This computer acts as an interface between the SCOOT computer and the signal controller unit out in the field. This computer is shown in Figure 4.6 as the “Controller Interface Computer.” For this research, SCOOT had to be connected to CORSIM. The SCOOT-CORSIM interface program developed at the University of Utah Traffic Lab was used for this purpose. [7]. This program enabled testing of SCOOT in a CORSIM simulated environment.

Figure 4.7 shows the interface between SCOOT and CORSIM as the "Interface Device Emulator." CORSIM and the interface program run on an IBM Compatible PC operating on Microsoft® Windows 2000, while SCOOT operates on a Digital Equipment Corporation® Alpha machine with OpenVMS as the operating system. The arrows in the figure represent the direction in which information flows.

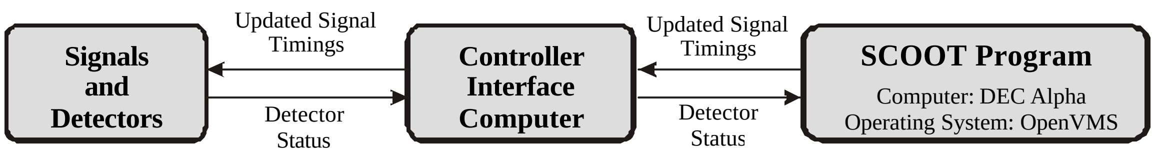


FIGURE 4.6: SCOOT in a field environment

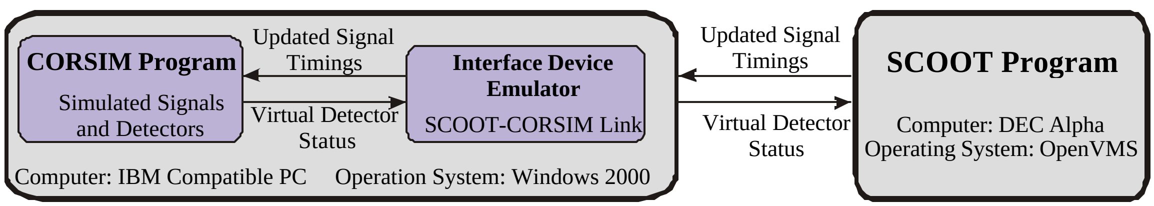


FIGURE 4.7: Schematic Representation of the SCOOT-CORSIM Interface

Just as detector information is communicated to SCOOT in an actual field installation through the controller interface computer, real-time detector information from CORSIM simulated detectors was sent to SCOOT through this interface program. SCOOT then computed optimal signal timings for the detected flow. These updated signal timings were then sent back to CORSIM which implemented these timings instantaneously. Detailed information regarding the SCOOT-CORSIM interface program, its function and its source code written in Microsoft® Developer's Studio® is documented in an internal working paper of the Utah Traffic Lab [52].

SCOOT Validation

Validation is the process of setting up SCOOT so it can accurately model the traffic flow behavior on the street, which in this case, was the simulated network and corridor. Validation is a one-time process during SCOOT system set up. Validation parameters depend on the geometry, detector layout, and operating characteristics of the network, but are independent of traffic volume. Thus, once SCOOT was validated at 0.7 v/c ratio, no further validation was needed.

There were seven parameters that had to be validated in SCOOT: main downstream link, default offset, journey time, maximum queue clear time, start lag, end lag, and saturation occupancy. Start lag is the time elapsed between the starting of a phase and the first vehicle crossing the stop-line. End lag is the time elapsed between the ending of a phase and the last vehicles crossing the stop-line. For a simulated network, the start lag and end lag depended on the setting in CORSIM. Once they were fixed in CORSIM they did not need revalidation in SCOOT. The main downstream link of an upstream link is the link into which an upstream link discharges most of its traffic. The main downstream link was coded during the SCOOT setup. As this value did not change during the two-hour simulation, the main downstream link parameter was not validated. The default offset is needed in case of faulty detectors. However, as simulated detectors do not turn faulty, validation of default offset was not needed.

The remaining three parameters: journey time, maximum queue clear time and saturation occupancy did require validation. Journey time is the time taken by a vehicle to travel from the upstream detector to the stop-line at free flow speed. Maximum queue cle ar time is the time required to clear the maximum queue while saturation occupancy is the queue discharge rate. These parameters typically are validated by field observation whenever SCOOT is installed in the field. However, in a simulated environment, validation is based on observations from the simulation output file.

In this research, the SCOOT system was validated for the corridor and the same parameters were used for the network. Nine validation iterations were done to achieve the desired accuracy. Figure 4.8 shows percent benefits in delay reduction after each subsequent validation attempt. Results showed that initially, SCOOT performed 219 percent worse than a Synchro fixed-time plan. This is likely because

SCOOT was not accurately predicting the queues and arrival-departure patterns, and was therefore unable to optimize corridor performance. Finally, after nine iterations, SCOOT accurately predicted queues and arrival-departure pattern thereby yielding 8 percent benefit over Synchro.

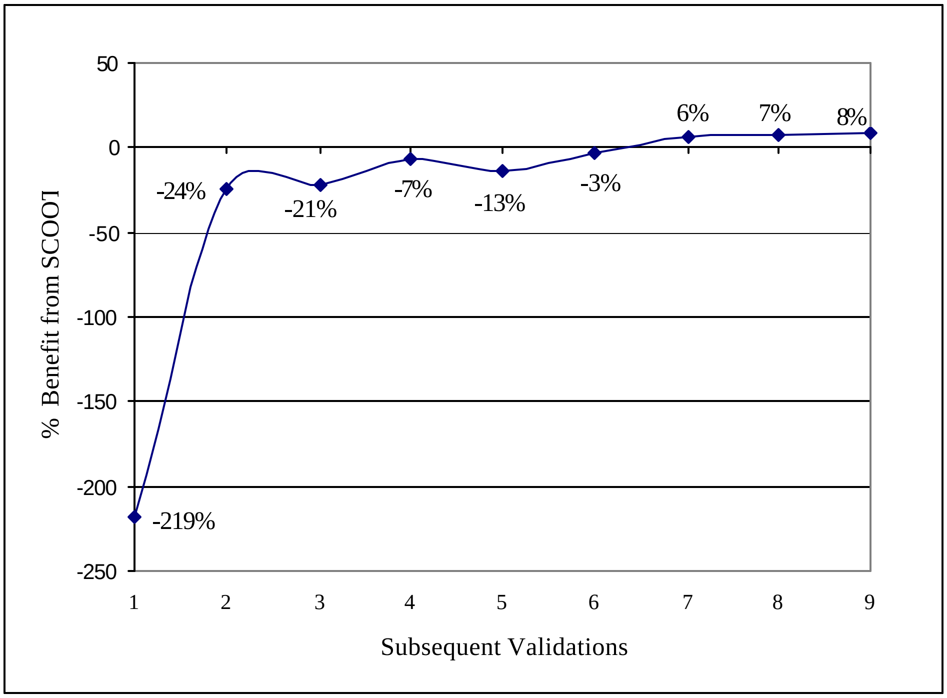


FIGURE 4.8 Benefits from subsequent validation attempts

REAL-WORLD NETWORKS AND CORRIDORS

Two real-world networks and corridors were modeled to establish validity of the test network and corridor results. Modeling and results of these real-world networks and corridors is described.

Salt Lake City Downtown Area Network and Corridor

Modeling

Twenty-eight intersections in Downtown Salt Lake City were modeled. This network was selected as it had an orthogonal grid layout, and had several major north-south and east-west corridors that intersected in the area. The downtown network with major corridors such as 400 South, State Street, and 700 East is shown in Fig.5.1.

The data was collected in the area before light rail construction began on 400 South. Turning movement counts were taken at five-minute intervals during the evening peak period of 4:00 to 6:00 p.m. for all intersections that were to be modeled. The five-minute interval size provided variation that more closely reflected a true network, rather than one-hour or 15-minute intervals, which mask some of the variation. Geometry data such as number of lanes, length of turn pockets, etc., was collected by field measurement and from aerial photographs.

Optimized signal timings plans were generated in Synchro and TRANSYT. The results are shown for both, although the Synchro generated comparison is the more conservative. Signal phasing was selected based on the existing phasing provided by UDOT. Minor intersections operated on a two-phase pattern while major intersections operated on a four-phase pattern. The downtown network was used for both the congestion comparison of FT and SCOOT and the incident assessment. The location of the assumed incident also is shown in Figure 5.1. It is important to note that the congestion analysis and incident analysis are independent to identify the impacts for each.

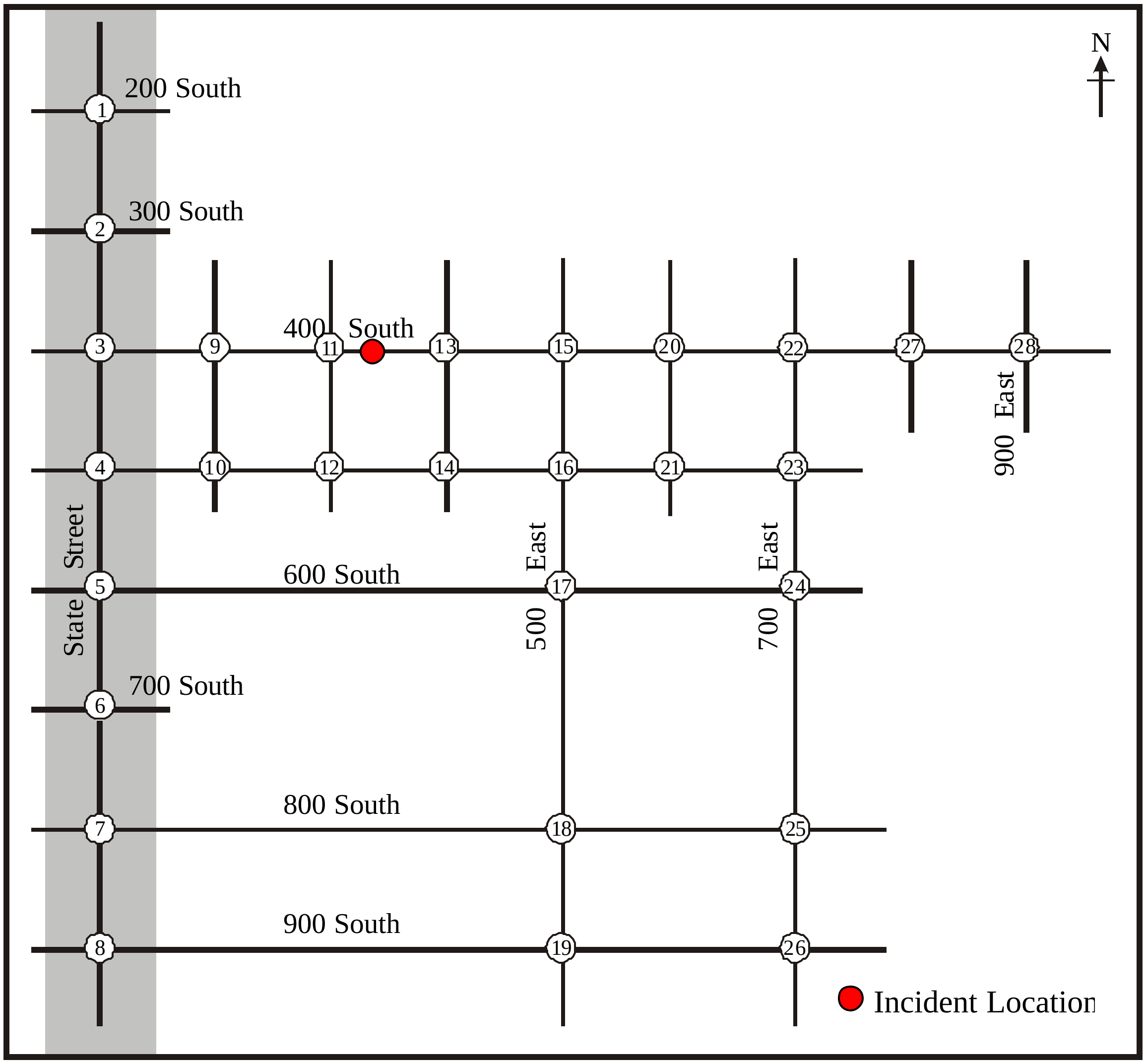


FIGURE 5.1: Downtown Salt Lake City Network and Corridor

Once geometry, volumes and timing plans were available, three CORSIM input files were generated: one operating Synchro timings, the second operating TRANSYT timings and the third one under SCOOT control. Similar to the test network, the downtown network was simulated for a two-hour 30-minute period. A 28-intersection SCOOT network also was built and validated. The CORSIM files were then run and results were extracted.

Eight intersections along the State Street corridor were modeled separately as an independent corridor analysis and are shown in the gray band in Figure 5.1. An eight-intersection SCOOT network also was built and validated. CORSIM input files were then run and results were extracted using ACCUSIM.

For the incident analysis, an incident is simulated on the eastbound 400 South corridor. The incident is simulated at the mid-block of 300 East and 400 East section. It should be noted here that v/c analysis of the downtown network showed that the network was operating at a 0.82 v/c ratio during the PM peak period. This value was computed by averaging the v/c ratios of all intersections.

Results

The results of the Salt Lake City downtown network and the State Street corridor are shown in Table 5.1 and Table 5.2 respectively.

TABLE 5.1: Benefit of SCOOT over fixed-time for Downtown Salt Lake City Network

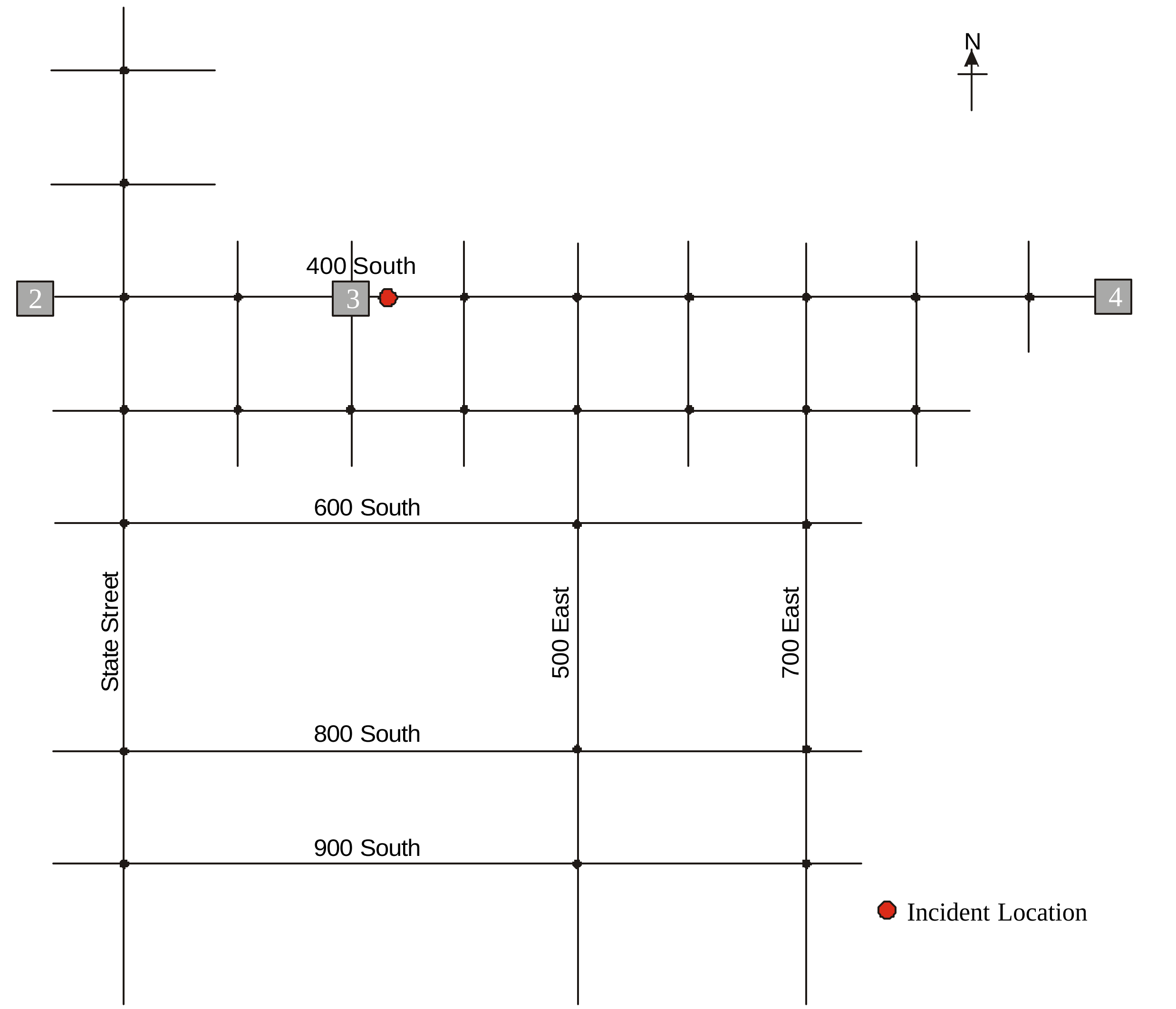
Measure of Effectiveness	**Benefit of SCOOT over Fixed-time (Synchro)**	**Benefit of SCOOT over Fixed-time (TRANSYT)**
Delay	23%	30%
Queue Length	10%	9%
Travel time	14%	18%

TABLE 5.2: Benefit of SCOOT over fixed-time for State Street Corridor

Measure of Effectiveness	**Benefit of SCOOT over Fixed-time (Synchro)**	**Benefit of SCOOT over Fixed-time (TRANSYT)**
Delay	14%	20%
Queue Length	5%	7%
Travel time	5%	8%

Results indicate that SCOOT improved network and corridor performance as compared to Synchro generated fixed-time plans. Delay benefits from SCOOT at individual intersections were as high as 50 percent when compared to Synchro. Benefits from queue length and travel time reduction by SCOOT over Synchro were as high as 43 percent and 19 percent respectively. Detailed results of delay and queue length at each intersection, and corridor travel times for downtown network and State Street are given in Appendix A. Overall benefits for the network and corridor were much higher when SCOOT was compared to TRANSYT.

When an incident is simulated, MOEs used are divided at network level, corridor level and intersection level MOEs. Figure 5.2 shows the network and the corresponding MOEs used in this research. Table 5.3 shows the benefits of SCOOT control over Synchro optimized FT control.



1. Total network delay at the end of 2 hour simulation in vehicle hours
2. Total travel time from node 2 to node 4 at the end of 2 hour simulation in seconds

MOEs
used in the study

3. Total intersection delay at the node 2 at the end of 2 hour simulation in vehicle hours
4. Average queue length on the southbound approach at node 2 at he end of 2 hour simulation in feet

FIGURE 5.2: Network and MOEs used in the study

TABLE 5.3: Benefits of SCOOT over SYNCHRO optimized FT on Downtown Network

MOE	No Incident			15-Minute Incident		
	SYNCHRO	SCOOT	Benefits	SYNCHRO	SCOOT	Benefits
Network Delay (Veh-Hrs)	1417.3	1067.8	24.7%	1598.2	1172.6	26.6%
Travel Time (Sec.)	247	206	16.6%	264	212	19.7%
Intersection Delay (Veh-Hrs)	15.4	11.3	26.6%	17.2	12.3	28.5%
Queue Length (ft.)	3240	2740	15.4%	3580	2880	19.6%
MOE	**30-Minute Incident**			**45-Minute Incident**		
	SYNCHRO	SCOOT	Benefits	SYNCHRO	SCOOT	Benefits
Network Delay (Veh-Hrs)	1663.8	1207.8	27.4%	1763.8	1263.9	28.3%
Travel Time (Sec.)	287	224	22.0%	302	233	22.8%
Intersection Delay (Veh-Hrs)	18.2	12.8	29.7%	19.2	13.3	30.7%
Queue Length (ft.)	3820	2960	22.5%	4220	3200	24.2%

The benefits of SCOOT in network delay reduction are approximately 25 percent, during no-incident scenario. The benefits for 15-minute incident scenario had a significant leap to 26.6 percent. For higher durations of 30 and 45 minutes, the benefits were marginally higher at 27.4 percent and 28.3 percent. This is because, the 15-minute incident occurred only during the peak volume and hence the effect of incident is prominent leading to significantly high benefits. During incident scenarios of 30- and 45-minute durations, the incident spread beyond the peak volume period and hence the effect of incident faded with time, leading to lower benefits. Similar reason is applicable for benefits in travel time, intersection delay, and queue length reductions. The benefits in travel time, Intersection delay, and queue length reduction reached as high as about 23 percent, 31 percent, and 24 percent respectively.

Results indicate that reduction in intersection delay did not increase significantly, since extra green time given in the incident affected direction, caused extra delay on the non affected direction bringing down the overall intersection delay benefits. Therefore, while the queue and travel time benefited from the SCOOT control, individual intersection delay changed little, but instead reassigned delay to the side street, reducing delay to the main street. Detailed results of travel time reduction, intersection delay and queue length are given in Appendix B.

Fort Union Area Network

Modeling

Fort Union Boulevard is in Murray City, a contiguous part of the Salt Lake Metropolitan region. The Fort Union Network comprises 13 intersections. This network was chosen because of its triangular configuration. It includes major corridors such as 900 East, Fort Union Boulevard, and Union Park Avenue, which are shown in Figure 5.3. The I-215 freeway that passes through the network also is modeled.

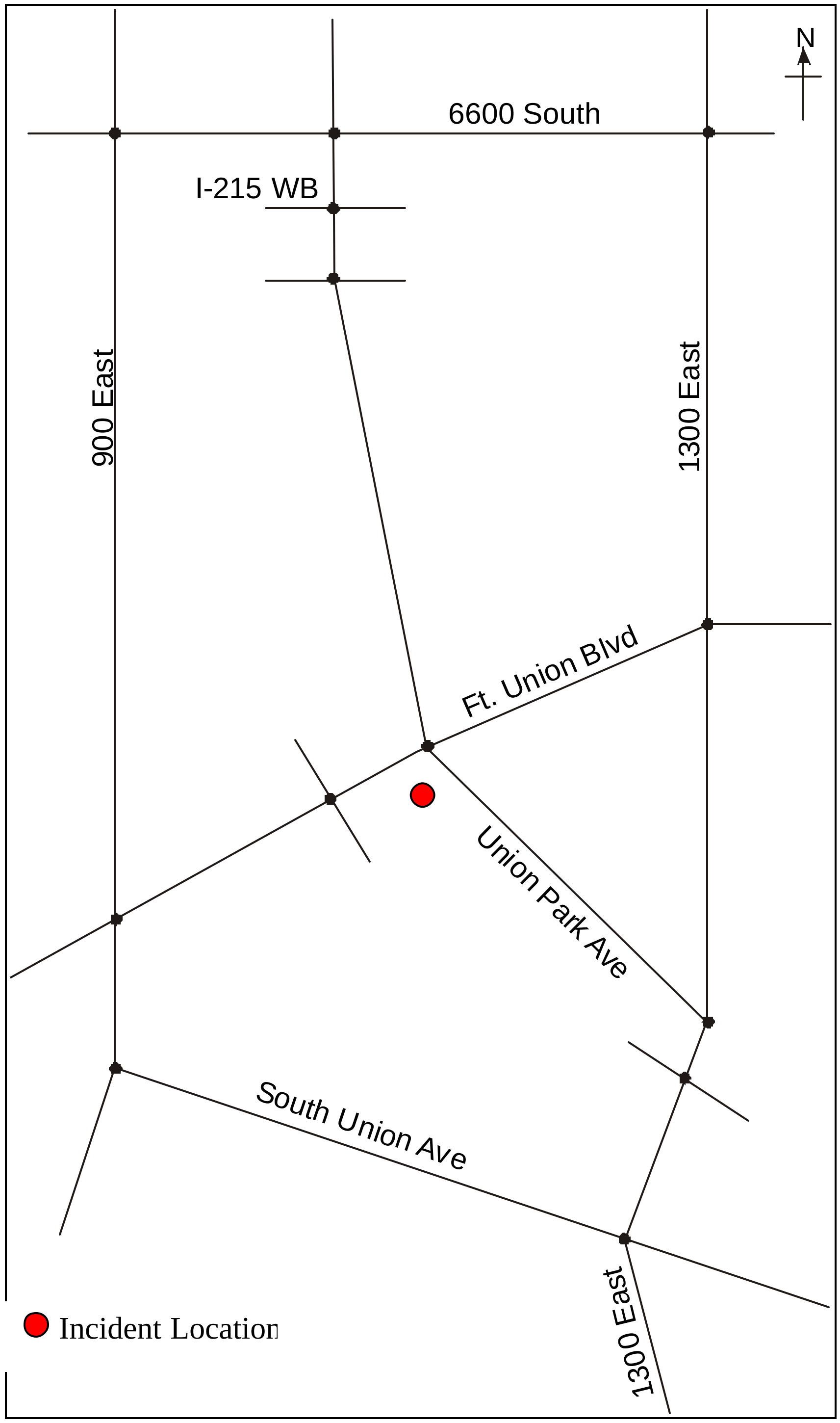


FIGURE 5.3: Fort Union Network

The data was collected in five-minute intervals primarily during the months of January and February of 2001. Data was collected during the PM peak hours of 4 to 6 p.m. However, data also was collected every month at the Fort Union Blvd and Union Park Ave intersection to observe monthly variations in traffic flow as described in Section 1. As with the Downtown network, an incident also is simulated to support the incident analysis. The incident is simulated at the mid-block of 1300 East and 7180 South. Figure 5.3 shows the schematic diagram of the Fort Union network area with the incident location. The performance of SCOOT is compared with FT operating with Synchro optimized signal timings.

Results

The MOEs considered in this study are divided at network level, corridor level, and intersection level MOEs. Figure 5.4 shows the network and the corresponding MOEs. Table 5.4 shows the benefits of SCOOT control over Synchro optimized FT control.

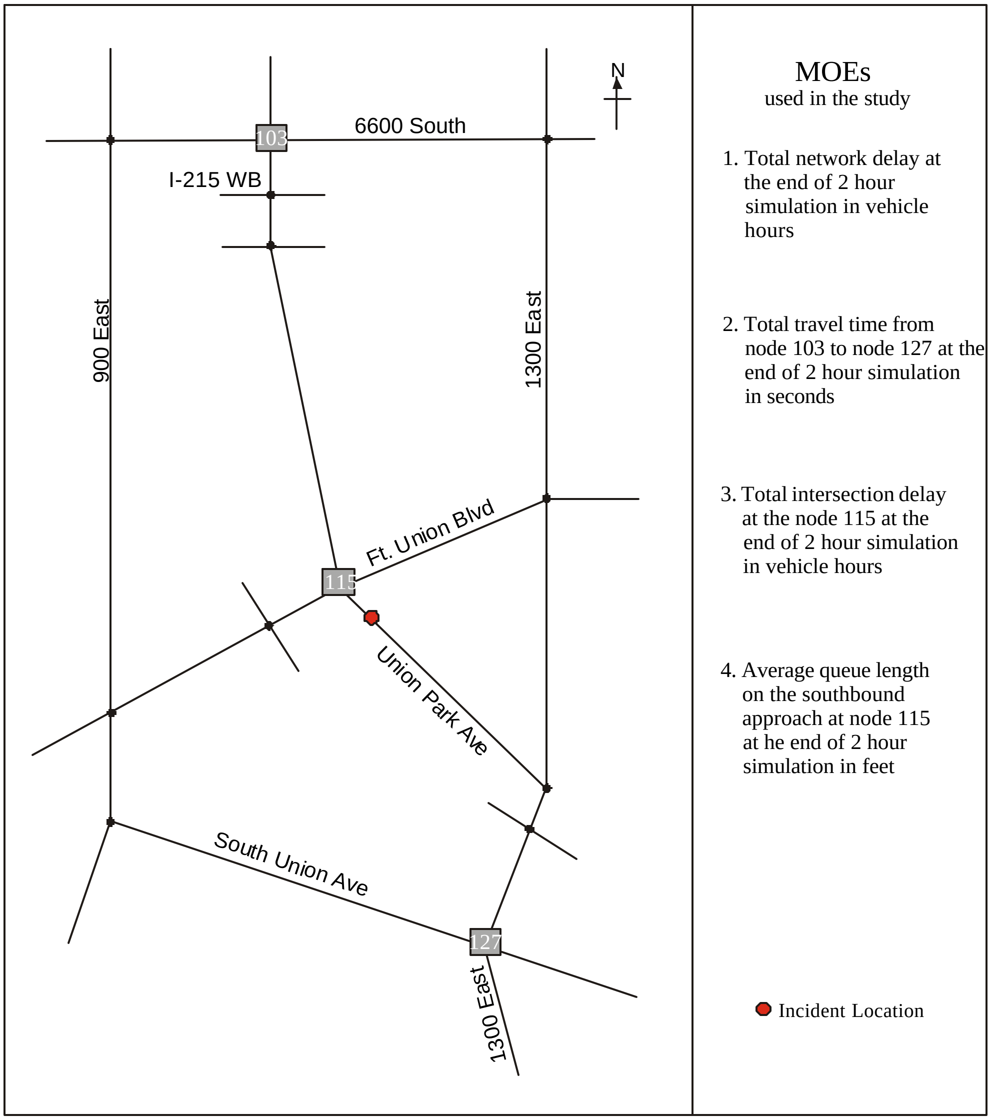


FIGURE 5.4: Network and MOEs used in the study

TABLE 5.4: Benefits of SCOOT over Synchro optimized FT on Fort Union Network

MOE	**No Incident**			**15-Minute Incident**		
	SYNCHRO	SCOOT	Benefits	SYNCHRO	SCOOT	Benefits
Network Delay (Veh-Hrs)	982.5	721.7	26.5%	1127.1	779.8	30.8%
Travel Time (Sec.)	293	267	8.9%	337	280	16.9%
Intersection Delay (Veh-Hrs)	13.7	12.7	7.3%	16.8	14.6	13.1%
Queue Length (ft.)	4760	4580	3.8%	5660	4600	18.7%
MOE	**30-Minute Incident**			**45-Minute Incident**		
	SYNCHRO	SCOOT	Benefits	SYNCHRO	SCOOT	Benefits
Network Delay (Veh-Hrs)	1197.4	812.4	32.2%	1254.7	813.1	35.2%
Travel Time (Sec.)	357	291	18.5%	379	302	20.3%
Intersection Delay (Veh-Hrs)	18.2	15.2	16.5%	19.5	16.1	17.4%
Queue Length (ft.)	6020	4720	21.6%	6220	4780	23.2%

The benefits of SCOOT in network delay reduction during no-incident scenario are approximately 27 percent. The benefits for 15-minute incident scenarios had a significant leap to 31 percent. For higher durations of 30 and 45 minutes, the benefits were marginally higher at 32 percent and 35 percent. This is because, the 15-minute incident occurred only during the peak volume and hence, the effect of incident is prominent leading to significantly high benefits. During incident scenarios of 30- and

45-minute durations, the incident spread beyond the peak volume period and hence, the effect of incident faded with time, leading to lower benefits. Similar reason is applicable for benefits in travel time, intersection delay, and queue length reductions. The benefits in travel time, intersection delay, and queue length reduction reached as high as about 20 percent, 18 percent, and 23 percent respectively. Detailed results of travel time reduction, intersection delay and queue length are given in Appendix C.

E-Center Area Network and Corridor

Modeling

The Events Center (E-Center) is an entertainment complex located in West Valley City, about nine miles south of downtown Salt Lake City, Utah. It hosts sporting events and music concerts. This network was chosen as it surrounds the E-Center complex. Nine intersections spanning east-west corridors such as 3100 South and 3500 South, and north-south corridors such as 2700 West, 3200 West and Redwood Road were modeled in the network, while five of these intersections along 3500 South were modeled separately in the corridor that was a chopped down version of the network. Figure 5.5 shows the layout of the E-Center network and the gray band demarcates the 3500 South corridor. On ramps and off ramps to the I-215 freeway that passes through the network were also incorporated.

Geometry of the network was collected by field observations and from aerial photographs. Traffic volume data for was collected in five-minute intervals during an event at E-Center from 5 to 7 p.m. Average v/c ratio of the network was 0.83, computed by averaging the v/c ratios of intersections along major corridors, such as Redwood Road and 3500 South. A v/c ratio of 0.83, as calculated here, might seem to be low for event conditions. However, this is probably because speeds were low, resulting in low volume measurements. Accurate field data of queue lengths can be used to calibrate congested conditions, but due to limited resources, such detailed data was not collected making this calibration impossible. This limitation did not affect the research results, as conditions were same for fixed-time and SCOOT control thereby ensuring a fair comparison between the two control strategies.

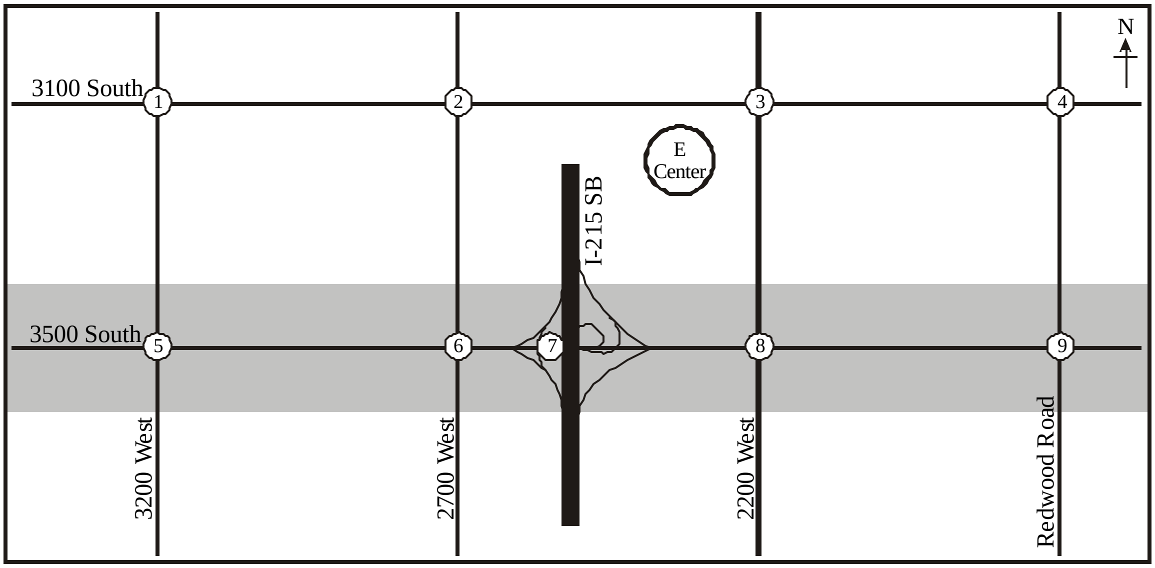


FIGURE 5.5: E-Center Area Network and Corridor

Results

The results of the E-Center network and 3500 South corridor are shown in Table 5.5 and Table 5.6, respectively.

TABLE 5.5: Benefit of SCOOT over fixed-time for E-Center area network

Measure of Effectiveness	% Benefit of SCOOT over Fixed-time (Synchro)	% Benefit of SCOOT over Fixed-time (TRANSYT)
Delay	15	36
Queue Length	10	25
Travel time	7	14

TABLE 5.6: Benefit of SCOOT over fixed-time for 3500 South corridor

Measure of Effectiveness	% Benefit of SCOOT over Fixed-time (Synchro)	% Benefit of SCOOT over Fixed-time (TRANSYT)
Delay	11	29
Queue Length	10	15
Travel time	8	14

Similar to previously described modeling, results form E-Center Area network and corridor also indicate that SCOOT improved network performance as compared to Synchro generated fixed-time plans. Delay benefits from SCOOT at individual intersections were as high as 46 percent when compared to Synchro. Benefits from queue length and travel time reduction by SCOOT over Synchro were as high as 38 percent and 11 percent respectively. Detailed results of delay and queue length at each intersection, and corridor travel times for E-Center network and 3500 South are given in Appendix D. Again, overall benefits for the network and corridor were much higher when SCOOT was compared to TRANSYT.

Bangerter Highway Corridor

Modeling

The Bangerter Highway is a major north-south arterial, which runs the full length of the Salt Lake Valley. The simulated section of Bangerter Highway extends from 2400 South to 9000 South with 11 signalized intersections. The arterial is modeled in VISSIM. Traffic flow information was collected from 4 to 6 p.m. in five-minute intervals.

Three traffic signal control regimes (Existing Timing, Optimized Timing, and SCOOT) are evaluated. Existing timing is an actuated-coordinated signal control regime currently used on Bangerter Highway. This was provided from the Mr. Mark Parry at the UDOT TOC. Based on field counts, the timing plan provided was sub-optimal. This is likely due to the variation in flow and the aging of signal timing plans, particularly in this growing area of the Salt Lake valley. New optimized actuated-coordinated timing plans were generated using Synchro. These are the "Optimized Timing" for the analysis. The three signal time plans are evaluated in VISSIM environment.

Results

Table 5.7 lists average vehicle-delays by intersection and for the network as a whole. The results indicate that SCOOT reduces vehicle delay by 16 sec or 25 percent when compared with the existing time, and by 6 sec or 12 percent when compared with the Optimized timing plan. Except for 2400 South and 4700 South, all the other intersections experienced average delay reductions ranging from 3 sec to 40 sec or from 6 percent to 63 percent when compared to the existing time plan. The average delay reductions ranges from 4 sec to 20 sec or 9 percent to 30 percent when compared to the optimized timing plan.

It should be noted that since SCOOT is a network-based optimizer, it is not uncommon for some intersection to operate worse, while others operate better. The net effect is a reduced network delay showing an overall benefit but one should not expect to see every intersection operate better under SCOOT control than with a FT plan. The Bangerter Highway results show that SCOOT performs better than the Optimized actuated-coordinated signal time plan.

TABLE 5.7: Benefit of SCOOT over fixed-time for Bangerter Highway

	Existing timing (sec/veh/int)	Optimized timing (sec/veh/int)	Scoot (sec/veh/int)	Percent Difference to Existing timing	Percent Difference to OT
All	63.66	53.85	47.65	+25%	+12%
2400 South	36.40	65.08	45.71	-26%	+30%
2700 South	64.60	30.24	24.15	+63%	+20%
3100 South	60.15	47.17	33.64	+44%	+29%
3500 South	50.81	43.32	48.00	+6%	-11%
4100 South	108.23	66.89	58.61	+46%	+12%
4700 South	75.17	86.33	94.02	-25%	-9%
5400 South	60.97	52.25	47.10	+23%	+10%
6200 South	63.63	51.19	37.76	+41%	+26%
7000 South	54.77	42.72	31.24	+43%	+27%
7800 South	59.00	50.04	43.97	+25%	+12%
9000 South	51.18	42.80	38.79	+24%	+9%

Note: + means a positive benefit, - means a negative benefit

BUS PRIORITY

The new construction of road capacity cannot meet the rapid increase of travel demand. Mass public transit has regained attention to solve the deteriorating congestion problem. Public transits can carry more passengers for the same amount of roadway space as private vehicles, and therefore, are substantially more efficient than private vehicles in road capacity usage. However, some public transits, like bus and light rail, share road right-of-way with private vehicles, and then suffer from the adverse effects of traffic congestion caused by private vehicles. Providing traffic signal priority is one of the promising subsidiary technologies to enhance the performances of transit, such as travel time and schedule reliability, then to improve service quality and attract more potential riders. A bus priority algorithm was included in SCOOT version 3.1 to integrate active priority to buses or other public transport vehicles with the common SCOOT UTC system [54]. Limited field trials on bus priority demonstrate the benefit on decreasing bus travel time and reducing bus delay at intersections [49,53,54]. But with most buses and light rails sharing the road with other vehicle traffic, priority policy affects the surrounding traffic. Whether the bus performance improvements are at the high cost of reducing the vehicle traffic performance is always a concern that keeps many traffic agencies skeptical of bus priority application in their own traffic networks. Since CORSIM does not have the transit modeling capabilities, a new SCOOT evaluation interface was created to link the actual SCOOT system to VISSIM [55]. As compared to the previously developed SCOOT-CORSIM interface, the added feature of this new interface is that the bus priority of SCOOT can be evaluated [56]. By the SCOOT-VISSIM interface, the adaptive signal control evaluates the ability to provide priority to bus traffic and identifies the impact to non-bus vehicles. The 400 South corridor in Salt Lake City, Utah was modeled in VISSIM. Taking the optimized actuated-coordinated signal timing (OT) as a baseline, a comparison of the person delay to all traffic, bus and all other traffic, (the term “vehicle” is used to identify all other “non-bus” traffic) separately under a variety of control regimes: OT, SCOOT control without bus priority facility activated (SWOB), and SCOOT control with bus priority facility activated (SWB). Note that person-delay is a more appropriate measure than vehicle-delay when assessing transit operations and therefore this MOE is used throughout this section of the report.

SCOOT Bus Priority

SCOOT's active bus priority either extends current green phase or recalls the green phase early to benefit buses. Two alternatives exist for extensions: central extension and local extension. Central extension uses the centralized SCOOT processing to determine the priority. Local extension grants the extension locally by the signal controller on street that can be programmed. Local extension avoids the communication delay between the SCOOT central computer and the local controller. SCOOT can be configured by node to allow/disallow each of these methods of priority. Selective Vehicle Detectors (i.e. bus loops and bus-borne transponders) or Automatic Vehicle Location can provide the on-line bus approaching information to SCOOT.

Buses are modeled queuing with other vehicles in SCOOT to consider the delay due to other vehicles. To avoid disrupting the signal coordination, "recovery" methods are available to allow the intersection to quickly return to normal SCOOT optimization. Operators can control priority based on node, approach and/or bus variation from schedule by a combination of parameters. Accuracy of bus journey time from detector to stop line is one critical factor for bus priority algorithm performance, although there are parameters allowing a degree of variability in bus journey time along the link. SCOOT does not model the time spent at a bus stop, so buses need to be detected after any bus stop on a link. Far-side stops allow for the proper priority methodologies and are more beneficial than near-side stops. As traffic flows approach over-saturated conditions, the priority can be restricted based on a target degree of saturation. An alternative bus priority strategy can also be used for saturated conditions, such as SCOOT "gating," a strategy to move congestion from major bus routes to the adjacent minor roadways. SCOOT's flexibility proved to be highly efficient on increasing travel speed and decreasing travel time, delays, stops, and fuel consumption. This was true in both field trials [58] and simulation evaluations when compared to the updated plan-based signal timing. Reported bus priority field trials using SCOOT showed benefits to buses with no significant negative impact to vehicle traffic. In the 10-intersection, Camden SCOOT area of London, 22 percent average bus delay saving per intersection was measured and 70 percent in light volumes using both extension and recall [49]. Combination of priority techniques can be applied to further improve the benefits. The field trial in the region of Twickenham near London displayed that SCOOT with both bus priority and gating reduces bus delays by an additional 6 percent than with bus priority alone [53].

Besides SCOOT, the adaptive control systems SCATS (Sydney Coordinated Adaptive Traffic System) and RHODES (Real-time, Hierarchical, Optimized, Distributed, and Effective System) also have introduced bus priority. The active priority strategies of SCATS provide 6-10 percent improvement in bus travel time with little imapct on travel times for other vehicles [59]. The "BUSAND" algorithm in RHODES provides bus priority considering the number of bus passengers and on/behind bus schedule. Evaluated in the CORSIM simulation environment, the algorithm can save approximately 19 percent average bus delay on main-street compared to semi-actuated control in CORSIM. But this is only slightly better than the result of RHODES control without bus priority [59].

The SCOOT-VISSIM Interface

VISSIM is a microscopic traffic simulation software developed for integrated traffic system including vehicle traffic, bus, rail transit, pedestrian, and bicyclists. The flexibility and convenience of setting transit routes and stops, the accuracy of modeling vehicle interaction such as yielding, stopping, and queuing, the flexibility of bus scheduling on departure and dwell time, 3D demonstration, and plenty of MOEs, all grant VISSIM the ability to simulate public transit [60]. Several simulation environments for evaluating adaptive traffic signal control systems have been developed, including SCOOT in CORSIM [56], RHODES in CORSIM [61], OPAC in CORSIM [62] and SCATS in VISSIM [63]. These models enable the adaptive signal control systems being evaluated in different simulation environments. Like the above simulation systems, a SCOOT-VISSIM interface is developed to act as a data exchange to communicate SCOOT and VISSIM. VISSIM consists of two parts: traffic simulator and signal state generator, which simulate traffic flow and determine signal phases, respectively. Signal Controller Junction (SCJ) defines the signal controller that controls the signal phases of the junction during simulation. SCJ allows external signal control system to supplement its own signal generator through setting the optional Vehicle Actuated Programming (VAP) module.

The SCOOT-VISSIM link is different from the Dynamic Link Library (DLL) SCOOT-CORSIM interface. The SCOOT-VISSIM link includes two parts: VAP module for signal controller, and communication module, both developed in VISUAL C++. The functions of VAP module include getting detector data from the SCJ, acting as a data exchange to communicate virtual detector data and updating signal phases between the SCJ and the communication module, and implementing new signal timing. The communication module performs as a data exchange to collect detector data from each VAP and send them to SCOOT, retrieve signal timing update of the whole network and then distributing them to the corresponding VAP. Dynamic Data Exchange (DDE) and Transmission Control Protocol / Internet Protocol (TCP/IP) are two kinds of communication technique used in the programming. This “fools” SCOOT into believing that it controls a real traffic network. The architecture and data flow of the SCOOT-VISSIM simulation environment is as the Figure 6.1.

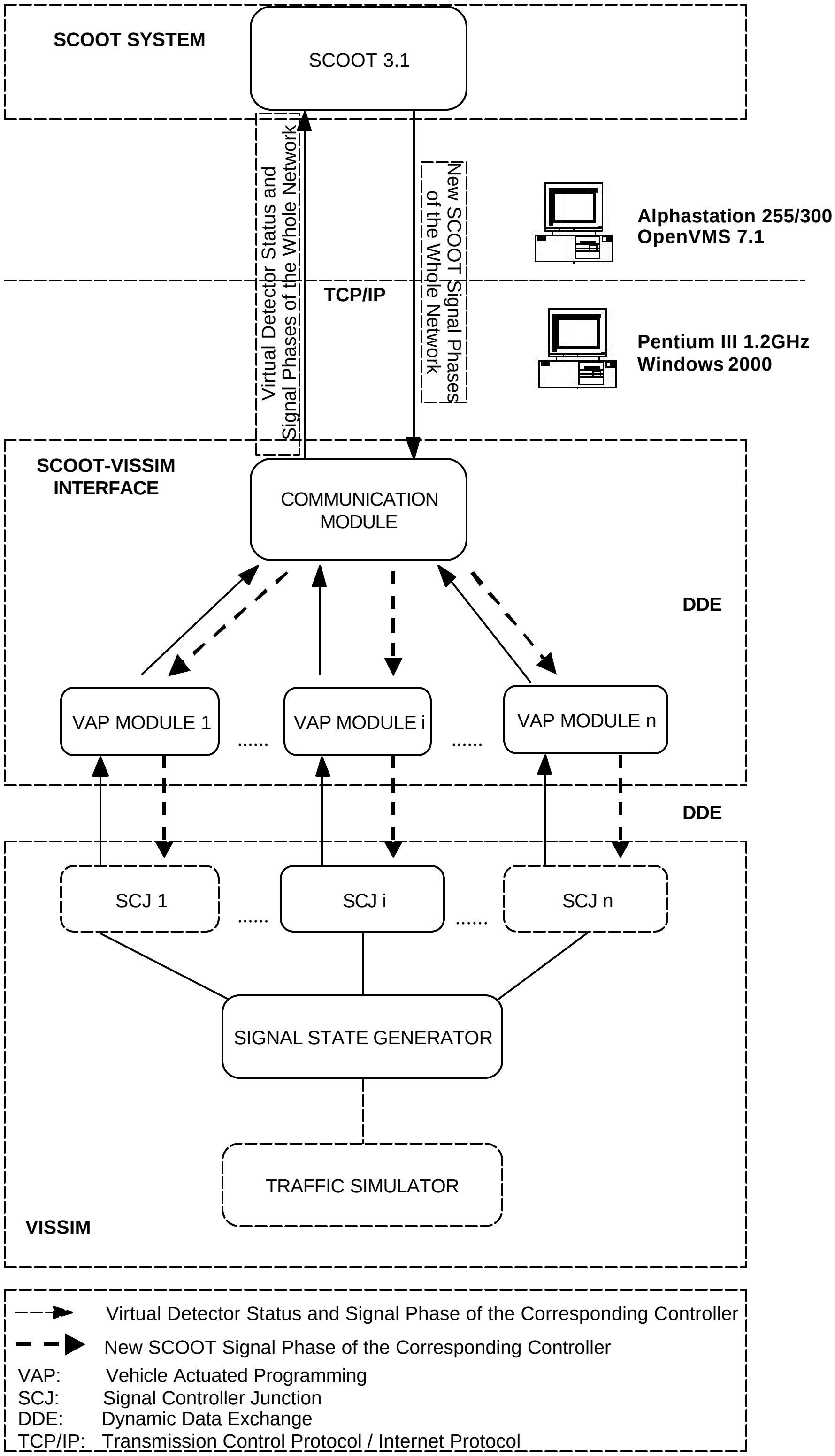


FIGURE 6.1: The data flow architecture of VISSIM-SCOOT Interface

One of the important tasks of the interface is to correctly map the traffic network in VISSIM and SCOOT. While the physical network is the same, coding the data structures that describe the traffic network elements, such as intersection, link, detector, and signal phase, are different. The interface also synchronizes communication between SCOOT and VISSIM. Since SCOOT operates in a real-time environment, the VISSIM simulation also must operate in real time (i.e. 1 s = 1 simulation second). This makes simulation efforts more time consuming than typical simulation activities.

SCOOT is not "plug and play." Validation is the critical process of setting up SCOOT so it can model properly the on-street traffic flow conditions of a specific network. As a one-time activity in SCOOT's initial set-up, SCOOT validation primarily is related to the geometry of the network and not the flow. The three primary parameters are maximum queue clear time, saturation occupancy, and journey time for buses and vehicles. These parameters typically are validated by field observation whenever SCOOT is installed field. In simulation environment, validation is based on observations from the simulation animation. The real-time simulation demonstration of VISSIM makes the validation similar to the actual process of installing an actual SCOOT system in the field.

The Simulated Corridor Data

The 400 South Corridor, shown in Figure 6.2, extends from 100E to 900E in Salt Lake City, Utah. Signalized intersections are spaced at 700-foot intervals. The nine intersections corridor was constructed in VISSIM on the basis of field verification to guarantee its geometric accuracy. The EB-WB direction is the coordinated direction. There are seven bi-directional bus routes in the corridor, shown as the dashed lines in Figure 6.2. They include five north-south routes, one east-west route, and one route that change from east-west to north-south. The actual bus frequency and bus stop number of each route is shown in Table 6.1.

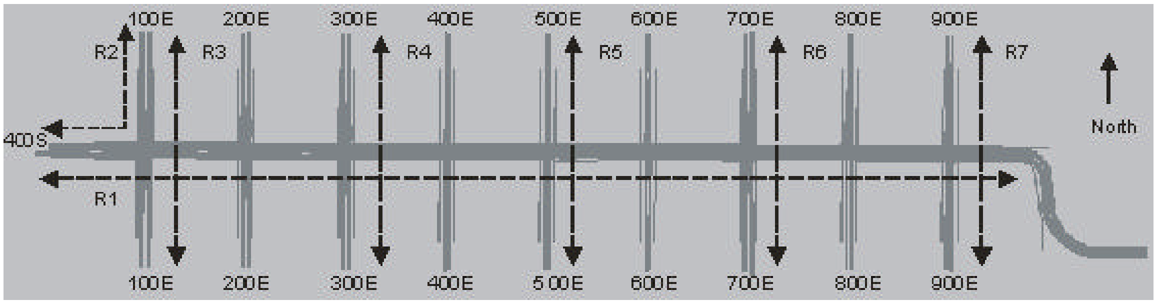


FIGURE 6.2: The 400 South VISSIM corridor in Salt Lake City, Utah

TABLE 6.1: The Bus Frequencies and Bus Stops of Seven Bus Routes

Bus Route		**4:00 – 5:00 PM**	**5:00 – 6:00 PM**	**Bus Stop Number (one direction)**
R1		10	11	4
R2	West to North	12	12	1
	North to West	18	17	1
R3		16	17	1
R4		3	4	1
R5		4	4	1
R6		12	9	1
R7		6	6	1

Note: Bus frequencies represent the total hourly bus flow per route on both directions

In addition to the bus routes, an east-west light rail, which is not considered in the modeling, is located on the 400 South corridor. The EB-WB direction has three through lanes and SB-NB has one-to-three through lines, depending on intersections. The delays on bus stops are not considered in MOEs. Vehicle detectors are located 600 feet from the stop line on through links and varied from 100 feet to 275 feet on different left turn pockets. Bus detectors are located 500 feet from the stop line on through links, except for a left turn bus detector, which is 120 feet from the stop line. An average of 35 persons on board each bus during the simulation is assumed.

Traffic flow was collected from 4 to 6 p.m. in five-minute intervals for a total of 24 time periods. The sum of the approach flows of the four critical intersections (100E, 300E, 700E, and 900E) is shown as the Figure 6.3. The figure shows that while the corridor is East-West oriented, southbound direction has the highest vehicle volume.

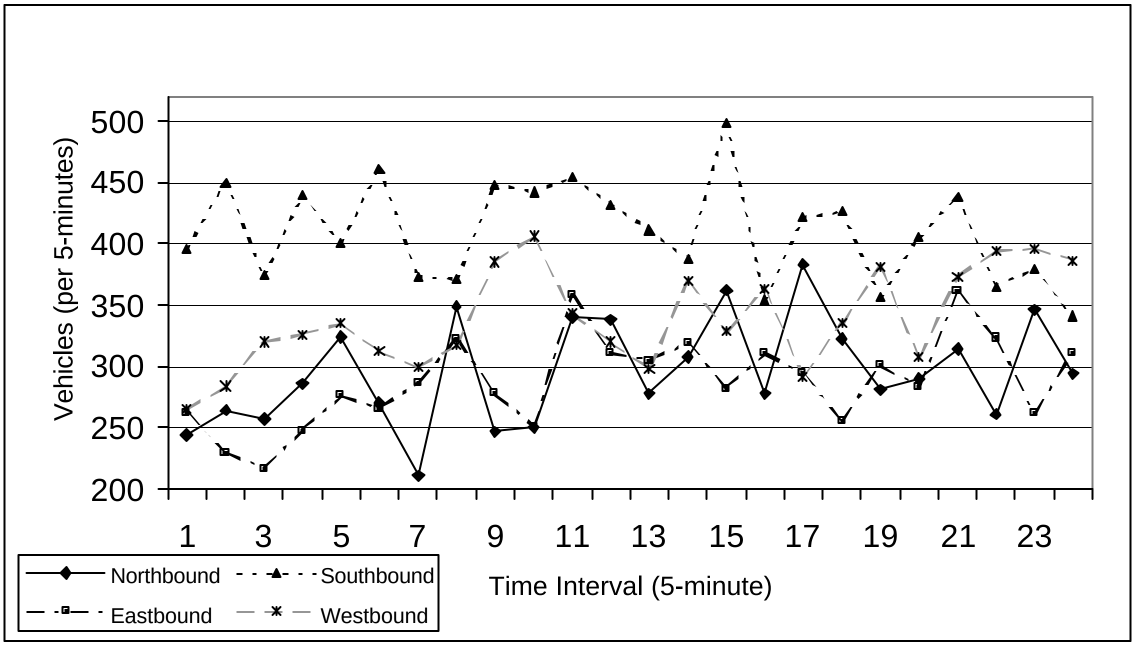
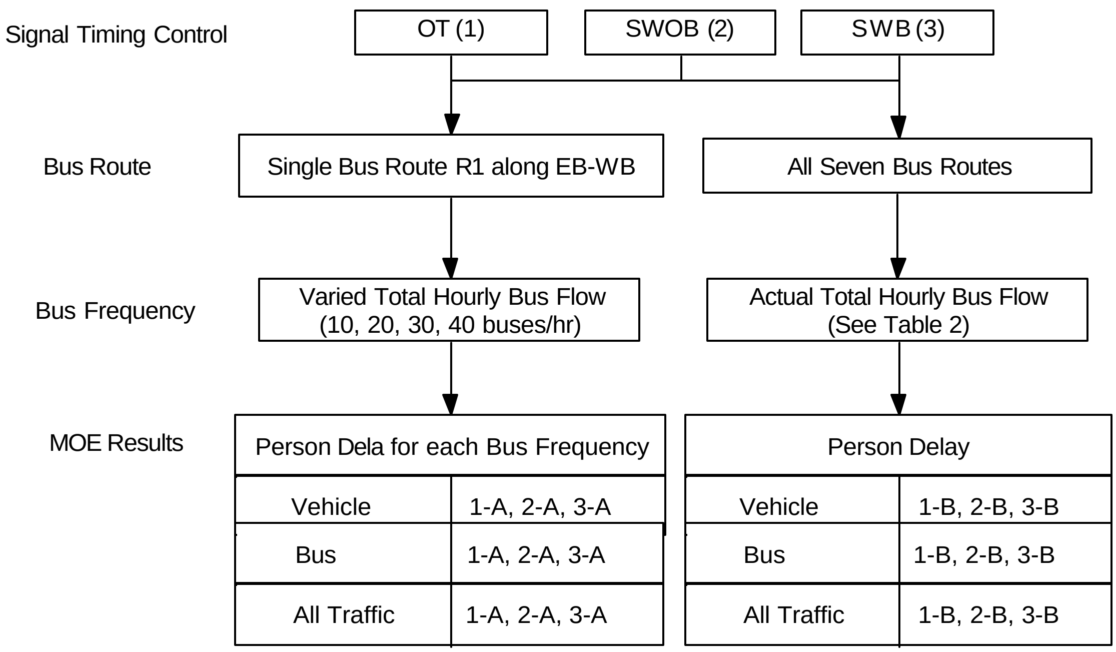


FIGURE 6.3: Direction flows of critical intersections

Evaluation Design

Under the above-mentioned traffic conditions of vehicle flow, geometry, and bus frequency; three traffic signal control regimes are evaluated: OT, SWOB, and SWB. OT is an optimized actuated-coordinated signal timing generated by SYNCHRO 5.0. For SWB, bus priorities are given on all directions. Whether the bus is behind schedule is not a special consideration. All three signal control regimes consider minimum pedestrian time.

Two evaluation plans are designed: all seven bus routes and only single bus route of EB-WB direction. All seven bus route plan represents real world condition. A single bus route (R1) of EB-WB, which removes all other six bus routes along NB-SB direction from the corridor, assesses the trade-off between vehicle benefits versus the EB-WB bus benefits with varying bus frequencies. The logical assumption is that because the signal coordination is temporally interrupted while SCOOT gives extension or recall to buses, the results may show extra delay to vehicle traffic. If bus frequency is higher, there should be more temporary interruptions happening, which will negatively impact vehicle traffic operations. The bus frequencies vary from 10 buses per hour to 40 buses per hour in 10 buses / hour intervals. These frequencies represent the total hourly bus flow per route on both directions. The artificial bus frequencies are made uniformly within each hour. This range of frequencies assesses the impact on SCOOT performance and how the interruption of optimized vehicle flow reacts to the artificial disruption of bus priority. Figure 6.4 shows the evaluation plans.



OT - the optimized actuated-coordinated signal timing
SWOB - SCOOT control without bus priority facility activated
SWB - SCOOT control with bus priority facility activated
Bus frequency represents the total hourly bus flow per route on both directions

FIGURE 6.4: SCOOT bus priority evaluation plan

Each evaluation combination takes five runs to provide mean and standard deviation of MOE results.

Results and Discussion

SCOOT Bus Priority Evaluation – All Seven Bus Routes

The assessment is made of the 400 South Corridor as a whole with all seven bus routes included. This addresses the SCOOT operations on an actual network. Table 6.2 shows that the impacts on average person delays of bus, vehicle and all traffic when all seven bus routes are included in the corridor.

TABLE 6.2: Person Delays for 400 South Corridor with Seven Bus Routes

		OT (sec/per/int)			SWOB (sec/per/int)			SWB (sec/per/int)		
		ALL	NB-SB	EB-WB	ALL	NB-SB	EB-WB	ALL	NB-SB	EB-WB
Person Delays	Bus	34.3/ 0.0	31.0/ 0.0	36.4/ 0.0	32.5/ 1.4	32.8/ 1.9	32.3/ 1.6	25.1/ 0.8	21.7/ 2.4	27.1/ 0.8
	Vehicle	27.8/ 0.0	25.6/ 0.1	29.3/ 0.0	21.9/ 0.4	24.4/ 0.2	20.1/ 0.6	23.4/ 0.7	26.4/ 1.2	21.2/ 0.9
	All Traffic	28.9/ 0.0	26.5/ 0.1	30.6/ 0.0	23.7/ 0.4	25.7/ 0.2	22.3/ 0.6	23.7/ 0.5	25.7/ 0.6	22.6/ 1.3
Percent Difference to OT	Bus	/	/	/	+5%	-6%	+11%	+27%	+30%	+26%
	Vehicle	/	/	/	+21%	+5%	+33%	+16%	-3%	+28%
	All Traffic	/	/	/	+18%	+3%	+27%	+18%	+3%	+26%

Note: NB – North Bound, SB – South Bound, EB- East Bound, WB- West Bound, ALL – Whole Corridor

Bus – bus only person delays, Vehicle - non-bus traffic person delays, All Traffic – all traffic person delays on the corridor

OT – the optimized actuated-coordinated signal timing, SWOB – SCOOT control without bus priority facility activated, SWB – SCOOT control with bus priority facility activated

#/# represents mean/standard deviation

+ means a positive benefit of SCOOT controls over OT, - means a negative benefit of SCOOT controls over OT

The results in Table 6.2 indicate that all three items (bus, vehicle and all traffic) of SCOOT controls experience a delay reduction over OT. The person delays of all traffic of SWOB and SWB are reduced by about 5.2 seconds from OT. The benefits mainly are from EB-WB direction delay reduction of both vehicles and buses compared to OT. Table 6.2 also shows that the SWB does reduce network delays to buses by 7.4 second but at a 1.5 second increase in vehicle person delays over SWOB. On NB-SB and EB-WB directions, SWB, compared to SWOB, reduces average person delay on bus at 11.1 second and 5.2 second separately. Vehicle person delays on both directions experience a small increase of about 1.5 second. Because bus passengers are only about 1/7 of people on the road in the evaluation, the benefits of bus are neutralized by the increase of vehicle person delay. The person delays of all traffic of both SWOB and SWB are almost the same. This reaches a balance at people ratio of bus to vehicle. If the average bus occupancy is less than 35 people, person delay of all traffic of SWB will be higher than SWOB. Otherwise, person delay of all traffic of SWB will be lower than SWOB. The analysis shows that SWB increases benefits to buses with only a small detriment to vehicle benefits compared to SWOB. Whether all traffic delay of SWB is better than SWOB depends on the people ratio of bus to vehicle.

SCOOT Bus Priority Evaluation – Single Bus Route (R1)

Table 6.3 shows the vehicle, bus, and all traffic person delays for the corridor controlled by OT, SWOB, and SWB. This is shown by varying bus frequency. The bus delays represent the single route concept in EB-WB, which is opposing the peak NB-SB flow direction. The delay is shown as average person delay per intersection.

TABLE 6.3: Person Delays of Varied Bus Frequencies with Only One Bus Route along EB-WB Direction

		OT (sec/per/int)			SWOB (sec/per/int)			SWB (sec/per/int)		
Bus Frequency	Vehicle-Type	ALL	NB-SB	EB-WB	ALL	NB-SB	EB-WB	ALL	NB-SB	EB-WB
10buses/hr	Bus	33.3/ 0.2	--	33.3/ 0.2	26.2/ 0.8	--	26.2/ 0.8	19.6/ 0.8	--	19.6/ 0.8
	Vehicle	27.7/ 0.0	25.3/ 0.0	29.5/ 0.0	21.8/ 0.3	24.1/ 0.3	20.2/ 0.7	22.2/ 0.9	26.0/ 0.7	19.4/ 1.2
	All Traffic	28.3/ 0.0	25.3/ 0.0	30.1/ 0.0	22.2/ 0.3	24.1/ 0.3	21.2/ 0.6	22.0/ 0.9	26.0/ 0.7	19.4/ 1.1
20buses/hr	Bus	33.4/ 0.0	--	33.4/ 0.0	26.3/ 1.8	--	26.3/ 1.8	19.7/ 0.6	--	19.7/ 0.6
	Vehicle	27.7/ 0.0	25.3/ 0.0	29.4/ 0.0	21.4/ 0.5	24.4/ 0.3	19.4/ 1.0	22.9/ 0.7	26.9/ 1.2	20.0/ 0.5
	All Traffic	28.7/ 0.0	25.3/ 0.0	30.5/ 0.0	22.3/ 0.5	24.4/ 0.3	21.2/ 0.7	22.4/ 0.5	26.9/ 1.2	19.9/ 0.4
30buses/hr	Bus	32.9/ 0.0	--	32.9/ 0.0	27.4/ 0.8	--	27.4/ 0.8	19.0/ 0.7	--	19.0/ 0.7
	Vehicle	27.7/ 0.0	25.3/ 0.0	29.5/ 0.0	22.2/ 0.2	24.2/ 0.4	20.2/ 0.3	24.1/ 1.5	29.2/ 1.5	20.4/ 1.4
	All Traffic	29.0/ 0.0	25.3/ 0.0	30.7/ 0.0	23.1/ 0.2	24.2/ 0.4	22.5/ 0.3	23.0/ 1.3	29.2/ 1.5	20.0/ 1.2
40buses/hr	Bus	32.6/ 0.0	--	29.0/ 0.0	26.1/ 1.1	--	26.1/ 1.1	19.5/ 0.2	--	19.5/ 0.2
	Vehicle	27.5/ 0.0	25.3/ 0.0	32.6/ 0.0	21.7/ 0.5	24.4/ 0.4	20.0/ 0.7	25.2/ 0.6	30.9/ 0.8	21.2/ 0.8
	All Traffic	29.0/ 0.0	25.3/ 0.0	30.5/ 0.0	23.0/ 0.7	24.4/ 0.4	22.3/ 0.9	23.7/ 0.4	30.9/ 0.8	20.6/ 0.5

Note: NB – North Bound, SB – South Bound, EB- East Bound, WB- West Bound, ALL – Whole corridor

Bus – bus only person delays, Vehicle - non-bus traffic person delays, All Traffic – all traffic person delays on the corridor

OT – the optimized actuated-coordinated signal timing, SWOB – SCOOT control without bus priority facility activated, SWB – SCOOT control with bus priority facility activated

Bus frequency represents the total hourly bus flow per route on both directions

-- No NB-SB bus routes run in this routing plan

#/# represents mean/standard deviation

Compared to OT, these results indicate that SWB and SWOB reduce person delays in bus, vehicle and all traffic. Although there is some variation as bus frequency varies, the total person delay benefit for all traffic is approximately six seconds per intersection for both SWOB and SWB against OT. The benefits are mainly from buses and vehicles on EB-WB direction where SWOB reduces delays of all traffic by 8.2 - 9.3 seconds and SWB by 9.9 - 10.7 seconds compared with OT. The results show that SCOOT controls are better in the coordination direction. On NB-SB, between OT and SWOB, person delays on vehicles are nearly the same with only one-second difference existing. However with bus frequencies increasing, SWB increases person delays of the vehicles by 0.7 – 5.6 seconds on NB-SB direction compared to OT. This is mainly because the vehicles on NB-SB are delayed by the priority given to buses in EB-WB direction. However, for SWB, the increases of vehicle delays on NB-SB are more than offset by the benefits of buses and vehicles on EB-WB direction. Figure 6.5 shows the person delay comparison between SWOB and SWB.

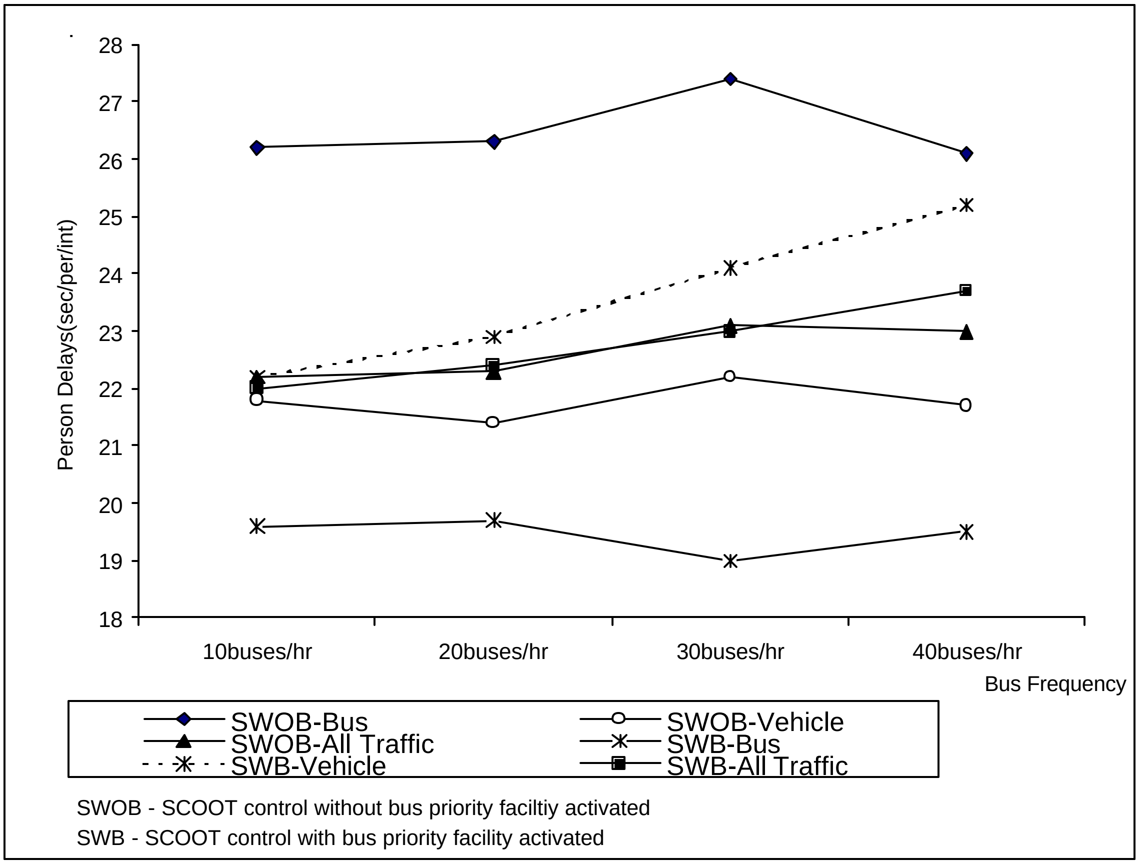


FIGURE 6.5: The comparison of person delays of whole corridor between SWOB and SWB with varied bus frequencies

With bus frequencies changing from 10 to 40 buses/hr, person delays of buses ranges from 26.1 – 27.4 seconds for SWOB, and 19.0 to 19.7 seconds for SWB. The results show that person delays of buses do not vary dramatically with different bus frequencies both for SWOB and SWB. SWB, compared to SWOB, reduces person delays of buses by 6.6 - 8.4 seconds. The bus frequencies do not affect the delay reduction substantially for the buses, but do for the person delays of vehicles on NB-SB direction for SWB. NB-SB direction is opposed to the bus priority direction. Compared to SWOB, SWB increases vehicle person delays by 1.9, 2.5, 5.0 and 6.5 on NB-SB respectively for four-frequency schema, but decreases the person delays of vehicles on EB-WB. Vehicles on EB-WB direction also benefit from bus priority. The delay reduction benefits of buses and vehicles on EB-WB are neutralized by the delay increases of vehicles on NB-SB for SWB. The result is that the person delays of all traffic of SWB are almost the same as those of SWOB. It is evident that bus frequency is an important factor affecting the tradeoff of person delays of vehicles by directions. The results show SWB can provide an excellent balance of benefits for both bus and vehicle traffic. It is necessary to state again that the ridership is an important factor deciding who is better for the person delays of all traffic between SWOB and SWB.

Summary

Using SCOOT-VISSIM interface, a nine-intersection corridor in urban Salt Lake City, Utah, is controlled by three different signal control strategies, including an optimal actuated-coordinated signal timing (OT), SCOOT control without bus priority facility activated (SWOB), and SCOOT control with bus priority facility activated (SWB). The actual corridor with seven bus routes is examined to determine SCOOT control performance and impacts of bus priority on the system. A single bus route with varying bus headways is evaluated to determine bus frequency impacts on the SCOOT performance. Benefits to vehicles and buses are monitored separately to determine how benefits to one may be detrimental to the other. The relative impacts to vehicles and buses are compared for SWB and SWOB to OT. The comparison demonstrates that SWB or SWOB performs better than OT. The person delays of all traffic of SWOB and SWB are about 18 percent or 5.2 second reduction over OT. When compared to OT, the benefits of SWB are 27 percent or 9.2-second reduced person delays for buses and 16 percent or 4.4-second reduced person delays for non-bus vehicles. SWOB is 5 percent or 1.8-second reduced person delays of buses and 21 percent or 5.9-second reduced person delays of non-bus vehicles against OT. The results show coordination direction (EB-WB) for vehicle and bus traffic receives large delay reductions under SCOOT control. Vehicle person delays on both directions experience a small increase of about 1.5 second for SWB compared with SWOB. In the single bus route evaluation, SWB compared to SWOB reduces bus person delays by 6.6 - 8.4 seconds for four-frequency schema. The reduction does not vary dramatically with different bus frequencies. The frequency does affect the person delays of vehicles on NB-SB direction, which is opposed to bus priority direction. Ridership is an important factor in deciding which option is better for person delays of all traffic between SWOB and SWB. Overall, SWB improves traffic performance on both bus and vehicle traffic relative to OT.

VARIABILITY ANALYSIS

Multiple SCOOT runs

SCOOT was designed to operate in a real-world installation and therefore it could accept detector data and deliver signal timings only in real-time. This means that a two-hour 30-minute simulation would actually take two hours and 30 minutes to finish. Generally, multiple simulation runs are done for the same input file and results are averaged. Due to the large number of simulation runs that were required in this research, the real-time operation of SCOOT was a major constraint and only one run per input file was done.

To examine the variation in output resulting from multiple SCOOT runs using the same CORSIM input file, five runs for the Salt Lake City downtown network were performed. The network was operating at 0.82 v/c. This network was chosen as it was the largest of all networks included in this research and was assumed to have maximum potential for variation. Table 7.1 shows the total network delay for these five runs and the percent variation of Run #2 through Run#5 with respect to Run #1. Statistical analysis shown in Appendix E indicated that difference between these five runs was insignificant. The difference showed that one run, with the random seed generator locked, was sufficient for valid comparison and multiple runs with the same CORSIM input file were not required.

TABLE 7.1: Delay from multiple SCOOT runs with same CORSIM input file

	Run #1	**Run #2**	**Run #3**	**Run #4**	**Run #5**
Delay (veh-hrs)	644.9	652.2	651.3	646.0	649.4
Variation from Run #1	-	1.1%	1.0%	0.2%	0.7%

Daily Traffic Variation

In CORSIM, user-entered random numbers generate driver responses to traffic choices, such as gap acceptance and lane blockage. Varying these random numbers by keeping traffic volumes constant would simulate traffic to represent different days at the same congestion level. This research used default CORSIM random numbers for comparing SCOOT to fixed-time control.

Though benefits reported in this research were based on default CORSIM random number seeds, it was felt necessary to ensure that similar benefits can be obtained from SCOOT on different days at a similar congestion level. Therefore, five CORSIM input files were prepared by varying random numbers, for the Salt Lake City downtown network. These files were then simulated under Synchro fixed-time and SCOOT control. MOEs were then extracted and percent benefit in delay reduction by SCOOT over Syncrho was computed. Table 7.2 shows the percent benefit in delay reduction for five random numbers that represent five days of traffic. Statistical analysis given in Appendix F indicated that there was negligible difference between the benefits realized from SCOOT over Syncrho for different traffic conditions. This constancy in benefits indicated that using only the default random number seed sufficiently represented the benefits for a particular congestion level, thereby eliminating the use of varying random number seeds.

TABLE 7.2: Delay Benefits from SCOOT over Syncrho using different random numbers

Random Number	7781 (CORSIM Default)	4231	4983	5859	5649
Synchro Delay (veh-hrs)	836.2	839.6	827.9	825.9	821.5
SCOOT Delay (veh-hrs)	644.9	650.2	635.8	640.4	635.9
% Benefit from Delay reduction	22.9	22.6	23.2	22.5	22.6
% Variation from defaut random number	-	-1.3	1.3	-1.7	-1.3

Cost-Benefit Analysis

Shown below is a generic equation that can be used to compute the annual social benefit.

$$S = \frac{C * T * V * H * D}{3600}$$

where,

S = Annual social benefit ($/year)

C = Price value of time ($/hour)

T = Delay savings (sec/veh)

V = Intersection volume (vehicles/hour)

H = Hours/day

D = Days/year

Figure 7.1 shows a graph that was developed based on the above equation. The variables were taken as C = $10.00 per hour, H = 16 hours per day and D = 261 days per year. The annual social benefit then was computed for different intersections volumes and delay savings. Each line on the plot corresponds to a particular volume. The values on the X-axis show the time saved per vehicle using adaptive control over fixed-time control. Values on the Y-axis indicate the total amount saved in thousands of dollars. To be conservative, yearly savings were computed based on a 16-hour day and a

261-day year. Using this chart, savings can be computed on an intersection basis. For example, if the average savings at an intersection was 8 sec/veh, and the volume through that intersection was 3500 veh/hr, then the annual user cost savings at this intersection based on a rate of $10 per hour would be $ 325,000. This is supported by literature that identifies that most SCOOT installations pay for themselves within one year, based on user cost savings [56].

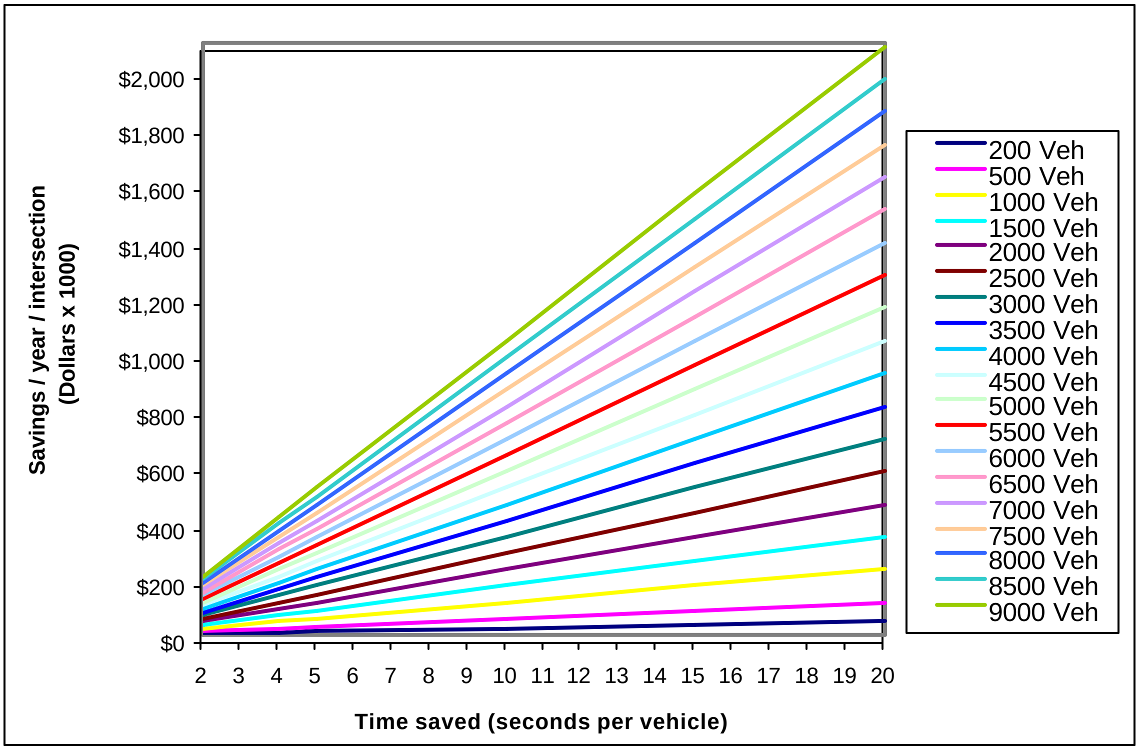


FIGURE 7.1 Savings of Adaptive Control Over Fixed Time Control

Equipment Requirements for SCOOT

Detection: Each detector returns occupancy values for each ¼ second. SCOOT claims to operate with most detection technologies and currently operates in field installations with inductive loop detectors and video image processing detection. A single six-foot detector by lane is preferred, although a single detector can be used to cover two adjacent lanes. SCOOT recently has been modified to improve its detection flexibility in the following way: SCOOT will support faulty detectors on side streets. When detectors turn faulty, SCOOT can use stored flow information from the ASTRID database to infer flows. It infers flows on minor links using flow information from surrounding major links.

Communications: SCOOT requires communications to and from the traffic signal controllers and from the detectors (that route through the controllers). The minimum bandwidth is 1200 bits per second (bps), which is enough to communicate with eight intersections and their detectors. These are low bandwidth communication demands. SCOOT can be installed with leased single telephone lines if necessary.

Controllers and Local Hardware: SCOOT has been made to work with NEMA, 170, 2070, TCT and TR0141 (UK) controllers.

Central Hardware: DIGITAL (recently purchased by COMPAQ) Alpha station computers are required to run the real-time optimization. These also act as a server to other workstations on the network that connect to the SCOOT systems. Remote workstations can have full control of the SCOOT system, through a 16 level username and password access system. Projection displays may also be useful for real-time monitoring. Simulation studies suggest that the benefits of SCOOT are lost if some 15 percent of the traffic sensors are faulty. Experience indicates that, with appropriate maintenance, sensor fault rates of well below 5 percent can be attained without undue difficulty.

RESULTS AND DISCUSSION

Due to the broad spectrum of analyses covered under this research, discussion immediately followed the results of individual experiments. This section, however, attempts to discuss the overall results.

Results showed that SCOOT improved network and corridor performance as compared to Synchro optimized fixed-time plans. Benefits of SCOOT over Synchro, for the network and corridor, increased with increase in congestion. However, these benefits were minimal as the network and corridor reached saturation. Figure 8.1 shows the profile of benefits in delay reduction from SCOOT over Synchro for the test network and corridor. Similar trends in benefits were also observed for queue length and travel time.

The profile for networks and corridors also shows that benefits from the network were consistently higher than benefits from the corridor. This is probably because along the corridor, none of the intersections were surrounded by SCOOT controlled nodes in all directions, while the network had four interior nodes that were surrounded by SCOOT controlled nodes in all directions. Higher benefits observed on these interior nodes probably contributed to higher benefits in the network than in the corridor.

The figure also displays two vertical lines at the corresponding congestion levels of E-Center and Downtown area networks, respectively. As per the test network results, benefits should be close to 16 percent for a network and 11 percent for a corridor. However, for the Downtown network, benefits were as high as 23 percent (shown as solid dot) for the network and 14 percent (shown as hollow dot) for the State Street corridor. This is probably because the test network and corridor assumed a 50-50 percent directional distribution of volume while Downtown and State Street had approximately 70-30 percent directional distribution. As higher number of vehicles passed in the coordinated direction, benefits from real-time coordination with volumes having a 70-30 percent directional distribution were much higher than benefits where volume had a 50-50 percent directional distribution. Benefits from delay reduction at the E-Center network (shown as a solid dot) and 3500 South corridor (shown as a hollow dot) more closely matched the values predicted by the test profiles as can be seen in Figure 8.1. This is probably because, E-Center being in the middle region of the network and corridor, the directional distribution was closer to 50-50 percent as traffic approached the E-Center from both sides before the beginning of the event.

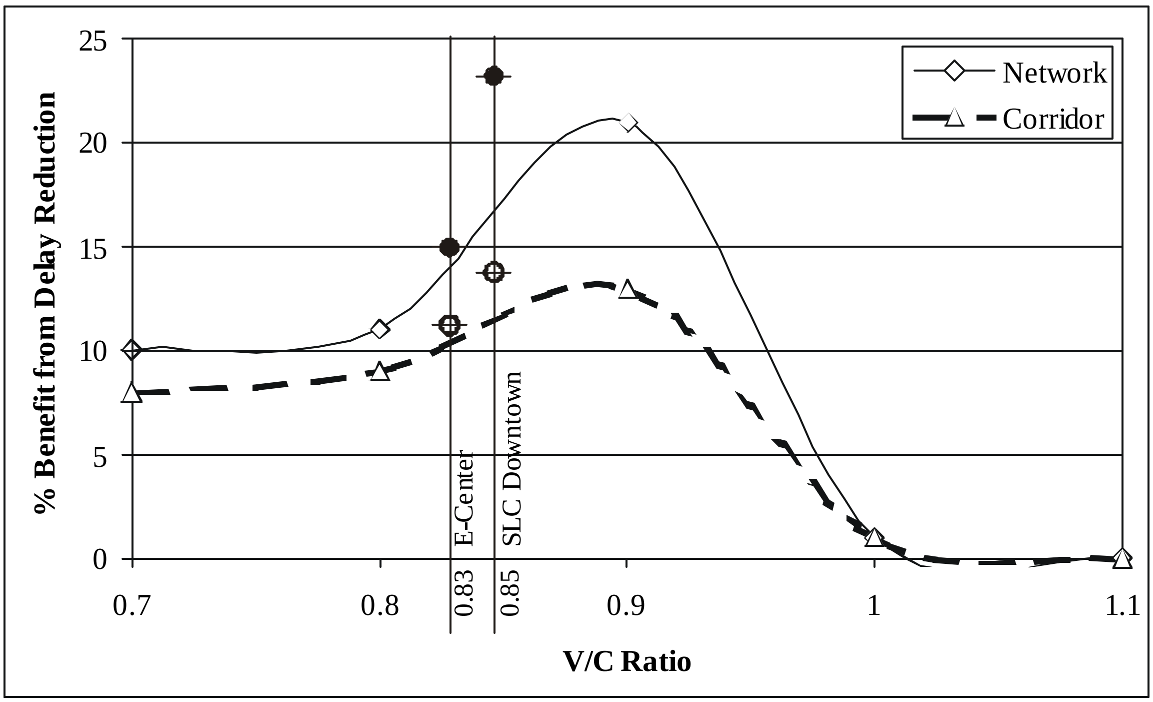


FIGURE 8.1: Benefits from Delay Reduction by SCOOT over Synchro

The incident analysis shows that SCOOT reduces delays over an updated plan-based signal control by 6.6 percent to 25.3 percent, depending on the congestion level and incident duration. The 15, 30, and 45-minute incident analysis shows that SCOOT provides benefits in travel time, intersection delay and queue length reduction are substantial. Figure 8.2 shows the SCOOT network delay benefits provided for the test, Fort Union and Downtown networks. The graphs for the other MOEs, travel time, queue length, and intersection delay, are provided in Appendix B and C.

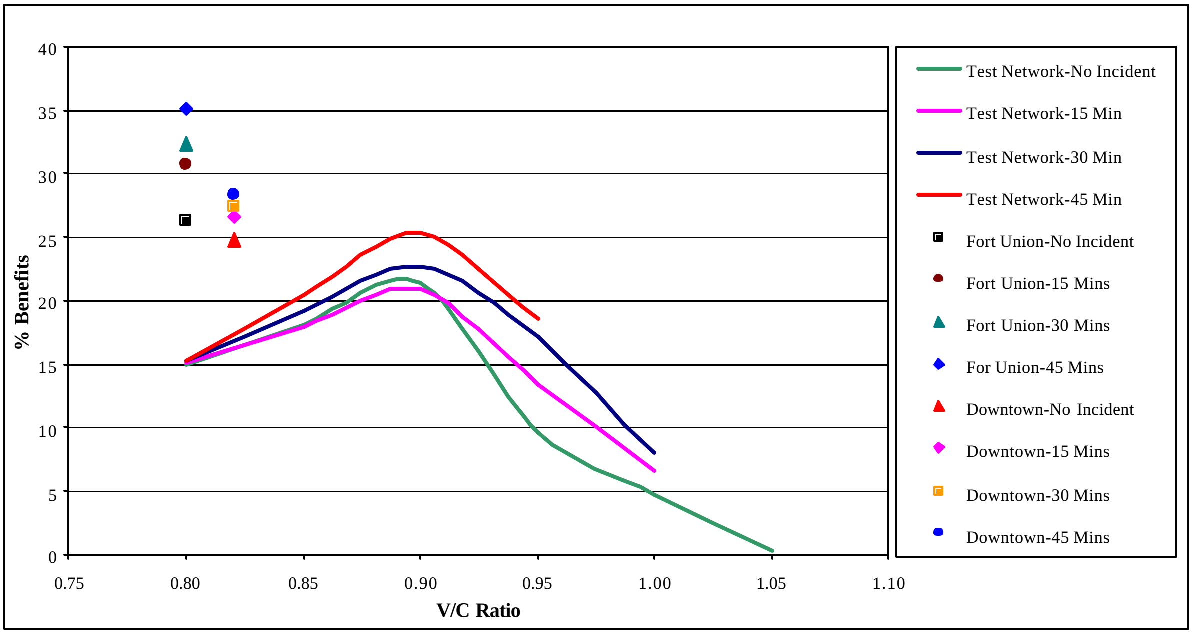


FIGURE 8.2: SCOOT Network Delay Benefits during Incidents

In the comparison of the results of real-world network and test network, there are a number of variables that affect the performance of a signal system. Some of the variables include:

- Congestion level of the incident affected intersection.
- v/c ratio of all the movements at the incident affected intersections.
- Congestion level of the surrounding intersections.
- Congestion level of the network.
- Direction distribution of the traffic on the networks.
- Average v/c ratio of the coordinated corridor.
- Spacing between the intersections.
- Critical intersection in the network.
- Geometry and signal phasing at each intersection
- Flow variation in networks.

Real-world networks and test networks differ in terms of the above variables. Hence, the results observed on test network do not exactly match with results on real-world networks. Since each network is unique and the benefits of adaptive control vary by network, the ability to simulate specific networks with software-in-the-loop (the actual adaptive control algorithms) allows for a more definitive process of estimating ATCS benefits.

CONCLUSIONS

The report provides documentation for the two-year assessment of adaptive signal control systems and their performance on Salt Lake specific networks. By developing an interface to allow adaptive signal control to be tested on Salt Lake City networks, the benefits of adaptive control during varying congestion and incidents is evaluated. In addition, the impact of bus priority, ramp meter interface, integration with ICONS, and an assessment of Bangerter Highway are included.

A review of the current state of adaptive signal control and operational performance shows that all the adaptive control systems provides similar benefits over an updated plan-based control. The potential benefits are identified from adaptive control on four sample Salt Lake Area networks. This was completed through the software interface that allowed the adaptive control system SCOOT to communicate and control the micro-simulators, CORSIM and VISSIM. The analysis examined a range of congestion levels on a test network to develop trends and benefits by congestion index. The benefits for networks and corridors are examined. The results show a substantial advantage of adaptive control over other plan-based timing operations. The most interesting results include a 21 percent reduction in delay for networks operating near 90 percent saturation and 14 percent reduction for corridors. Once demand exceeds capacity, then the benefits of adaptive control are limited to delaying the onset of congestion and quicker recovery from congestion but adaptive control should not be thought of as a magic wand. At or above saturation levels, adaptive control operates as an optimal timing plan would. The adaptive control operations during incidents shows 6 percent to 25 percent reduced network delays over other plan-based control. For the specific intersection near the incident, the benefits increase considerably as SCOOT reduces the propensity to reach grid-lock condition by reacting to building queues.

Bus priority is investigated along the 400 South corridor. Note that the measure of effectiveness changes from vehicle delay to person-delay with transit assessments. The bus priority algorithms are something that can be activated in SCOOT. As a base condition, the “without” bus priority is compared to the “with” bus priority to see how bus priority can be a detriment to the other vehicles. Along the 400

South corridor, SCOOT without bus priority reduces non-bus person-delay by 21 percent or 5.9 seconds per person and bus person-delay by 5 percent or 1.8 seconds per person. With bus priority, SCOOT reduces non-bus vehicle delays by 16 percent or 4.4 seconds per person and bus delays by 27 percent or 9.2 seconds. Overall, SCOOT reduced combined per person delay is an average 18 percent with or without the priority activated in the 400 South corridor. Therefore, the net benefit is the same for both conditions and the decision to implement bus priority is one of policy.

The modeling of Bangerter Highway shows that SCOOT performs better than optimized actuated-coordinated signal time plan. SCOOT reduces average vehicle delay by 16 sec or 25 percent when compared to the existing time plan, and by 6 sec or 12 percent when compared to an updated, optimized timing plan. Based on the existing communications to the Bangerter Highway, the system detectors present and coming on-line and the limited access nature of the corridor, Bangerter Highway is recommended as an ideal test location for an adaptive signal control system. UDOT is encouraged to pursue a field installation and evaluation.

In regard to ramp metering controlled by adaptive control, this currently is not available with any of the systems. There is some preliminary discussion and proposed research in this area at the federal level through the signal systems committee of the Transportation Research Board and may be the issue of a future NCHRP project.

FUTURE RESEARCH

With the positive findings of this research, a test field installation along Bangerter Highway is recommended. In addition, the following research ideas have been generated to continue to investigate the issues related to adaptive control. Some are specific to answering questions UDOT may find relevant while others are more general and would benefit the body of knowledge as a whole.

1. This research evaluates SCOOT's performance on typical grid networks. Though such a configuration is fairly common to see, modeling networks with other geometrical configurations or irregular geometry could help generalize the conclusions of this research. Triangular or hub-spoke geometry, is such an example.
2. When comparing SCOOT benefits on networks and corridors, it was found that benefits realized on networks was much higher. This was attributed to the higher benefits realized at nodes that were surrounded by SCOOT controlled nodes on all sides. As opposed to a 16-intersection network modeled here, modeling networks of different sizes at varying congestion levels could add another dimension to this research.
3. CORSIM provides limited support for pedestrians and are therefore not considered in this study. However, since SCOOT has now been linked to another simulation tool, VISSIM, impacts of pedestrian activity can be modeled more extensively. This would give a more accurate replication of downtown areas that have busy pedestrian activities.
4. The test network and corridor modeled here had a constant 1000-foot spacing between intersections. Varying the intersection spacing could help in examining how SCOOT would dynamically respond to factors such as platoon dispersion and other driver maneuvers.
5. There has been growing concern regarding air quality in urban areas. Algorithms in recent SCOOT versions can be modified to optimize network performance to mitigate effect of vehicles on air quality. SCOOT does this by optimizing for stops instead of delay. Comparing SCOOT's efficiency to plan-based signal control in reducing emissions would make interesting research.

6. Since networks are generally composed of corridors, the performance of SCOOT can be evaluated under two different scenarios, treating the whole network as single region and treating the network as a set of corridors
7. The sensitivity of SCOOT performance with varying location of incident in the mid block can be evaluated.
8. Upstream detection is the key to adaptive control. A sensitivity of SCOOT performance with varying detector location and loss of detectors could be evaluated to identify the benefit decay as detectors fail and timely maintenance is not present.

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APPENDICES

APPENDIX A

Analysis of Downtown Network and State Street

Benefits from Intersection Delay Reduction for Downtown Network

Intersection ID	2-hour Intersection Delay (veh-hrs)			% Benefit of SCOOT over Fixed-time (Synchro)	% Benefit of SCOOT over Fixed-time (TRANSYT)
	Fixed-time (Synchro)	Fixed-time (TRANSYT)	SCOOT		
1	33.0	31.8	27.7	16	13
2	30.0	43.9	21.2	29	52
3	56.0	51.5	37.6	33	27
4	16.3	24.0	17.4	-7	28
5	26.7	26.9	25.6	4	5
6	10.6	17.7	10.4	2	41
7	49.2	41.3	29.5	40	29
8	31.3	36.1	27.7	11	23
9	19.4	21.2	12.8	34	40
10	19.9	21.9	15.1	24	31
11	29.5	47.3	15.4	48	68
12	34.7	23.4	22.3	36	5
13	27.1	44.1	17.4	36	61
14	75.1	92.7	51.7	31	44
15	12.0	6.7	6.4	46	4
16	28.4	32.6	22.1	22	32
17	41.0	46.5	24.5	40	47
18	23.6	20.5	28.0	-19	-37
19	81.7	97.2	87.8	-7	10
20	103.8	93.4	51.5	50	45
21	8.0	5.4	9.3	-16	-72
22	6.8	9.0	8.7	-28	3
23	5.2	8.4	6.6	-27	22
24	10.1	20.3	8.1	20	60
25	15.4	11.8	19.9	-29	-69
26	20.0	18.1	18.6	7	-3
27	13.8	15.9	14.6	-6	8
28	7.5	7.7	6.7	11	14
Total	**836.2**	**917.2**	**644.9**	**23**	**30**

Benefits from Intersection Queue Length Reduction for Downtown Network

Intersection ID	Average Queue Length (feet)			% Benefit of SCOOT over Fixed-time (Synchro)	% Benefit of SCOOT over Fixed-time (TRANSYT)
	Fixed-time (Synchro)	Fixed-time (TRANSYT)	SCOOT		
1	1020	800	960	6	-20
2	780	980	700	10	29
3	1040	1020	900	13	12
4	600	620	540	10	13
5	660	580	600	9	-3
6	460	480	500	-9	-4
7	960	1020	760	21	25
8	760	740	780	-3	-5
9	520	580	540	-4	7
10	300	240	320	-7	-33
11	580	520	540	7	-4
12	340	300	280	18	7
13	700	740	560	20	24
14	260	340	340	-31	0
15	760	600	700	8	-17
16	380	580	420	-11	28
17	360	380	360	0	5
18	660	580	640	3	-10
19	700	820	700	0	15
20	680	900	700	-3	22
21	580	540	480	17	11
22	1240	1300	820	34	37
23	720	780	540	25	31
24	620	460	740	-19	-61
25	1280	1620	1500	-17	7
26	1740	1280	1000	43	22
27	460	260	420	9	-62
28	860	760	740	14	3
Total	**20020**	**19820**	**18080**	**10**	**9**

Benefits from Travel-time Reduction for Downtown Network

Corridor V/C	Average Travel Time (sec)						% Benefit of SCOOT over Fixed-time (Synchro)		% Benefit of SCOOT over Fixed-time (TRANSYT)	
	Fixed-time (Synchro)		Fixed-time (TRANSYT)		SCOOT					
Direction	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**
State Street	242	233	227	275	224	221	7	5	1	20
700 East	194	210	235	206	168	168	13	20	29	18
Direction	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**
400 South	278	303	324	275	225	247	19	18	31	10
Average							**14**		**18**	

Benefits from Intersection Delay Reduction for State Street Corridor

Intersection ID	2-hour Intersection Delay (veh-hrs)			% Benefit of SCOOT over Fixed-time (Synchro)	% Benefit of SCOOT over Fixed-time (TRANSYT)
	Fixed-time (Synchro)	Fixed-time (TRANSYT)	SCOOT		
1	34.0	36.0	28.6	16	21
2	28.8	38.7	25.2	12	35
3	56.8	60.4	52.5	7	13
4	25.2	30.3	19.2	24	37
5	25.2	26.9	22.9	9	15
6	10.2	16.7	11.8	-16	29
7	53.6	43.4	38.3	28	12
8	38.6	38.1	34.5	11	9
Total	**272.5**	**290.5**	**233.0**	**14**	**20**

Benefits from Queue Length Reduction for State Street Corridor

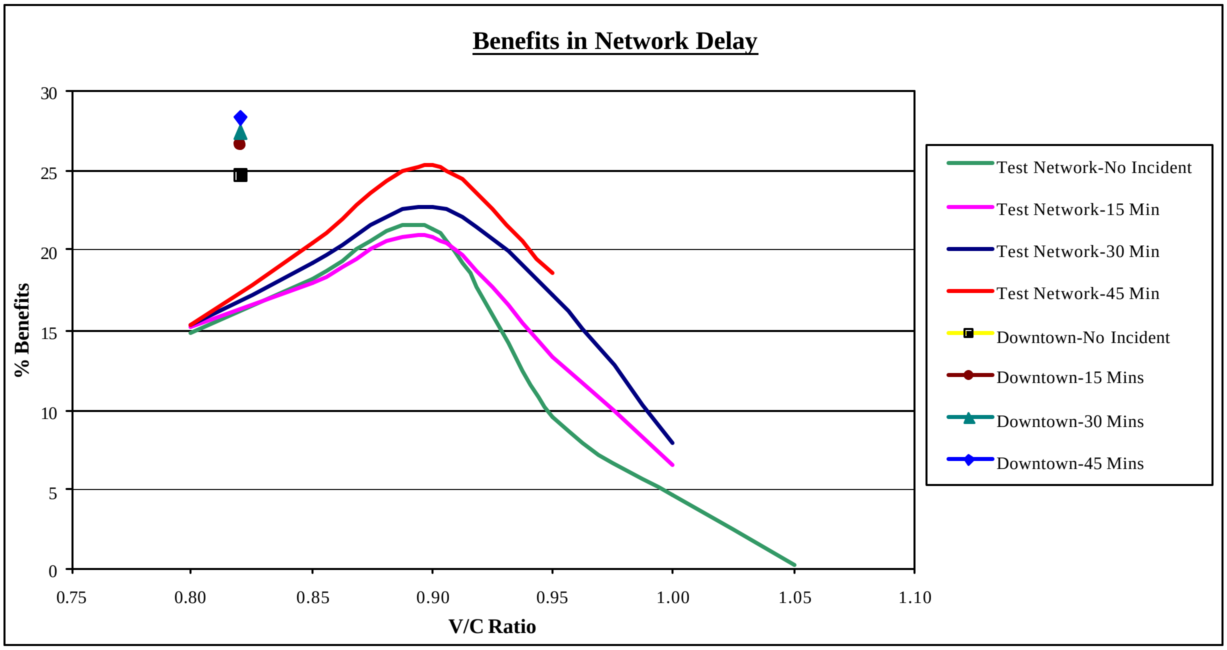
Intersection ID	Average Queue Length (feet)			% Benefit of SCOOT over Fixed-time (Synchro)	% Benefit of SCOOT over Fixed-time (TRANSYT)
	Fixed-time (Synchro)	Fixed-time (TRANSYT)	SCOOT		
1	1020	1100	940	8	15
2	760	840	700	8	17
3	980	1000	880	10	12
4	600	600	480	20	20
5	580	580	600	-3	-3
6	360	460	460	-28	0
7	900	960	840	7	13
8	900	660	880	2	-33
Total	**6100**	**6200**	**5780**	**5**	**7**

Benefits from Travel-time Reduction for Downtown Network

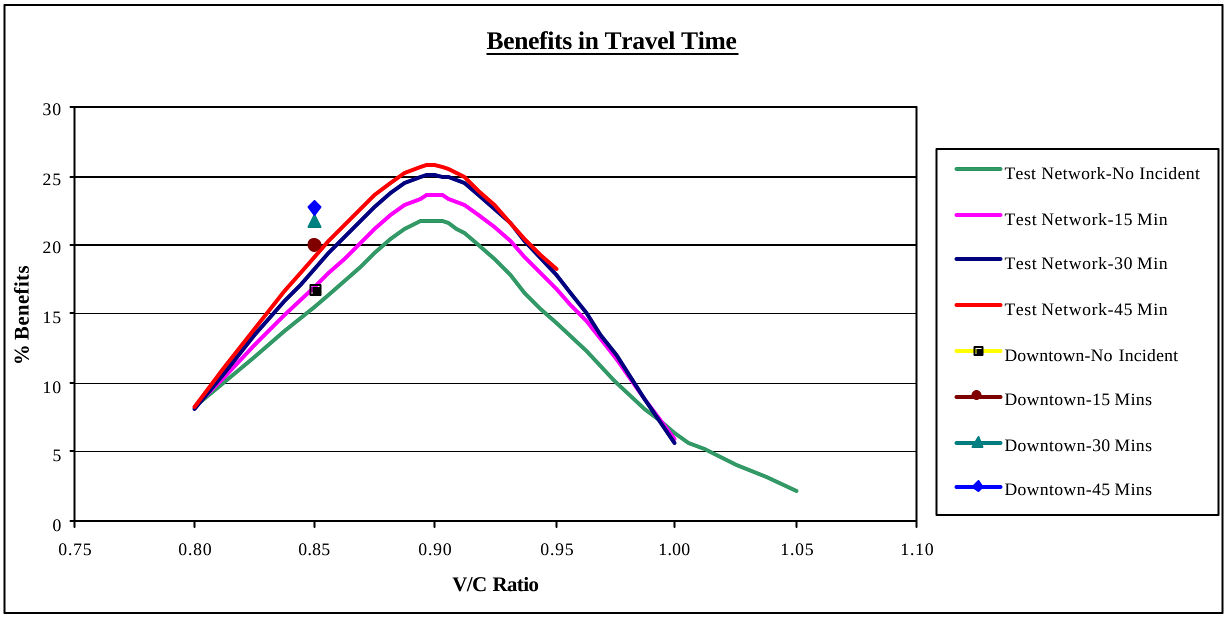
Corridor V/C	Average Travel Time (sec)						% Benefit of SCOOT over Fixed-time (Synchro)		% Benefit of SCOOT over Fixed-time (TRANSYT)	
	Fixed-time (Synchro)		Fixed-time (TRANSYT)		SCOOT					
Direction	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**
State Street	240	235	228	268	232	219	3	7	-2	18
Average							**5**		**8**	

APPENDIX B

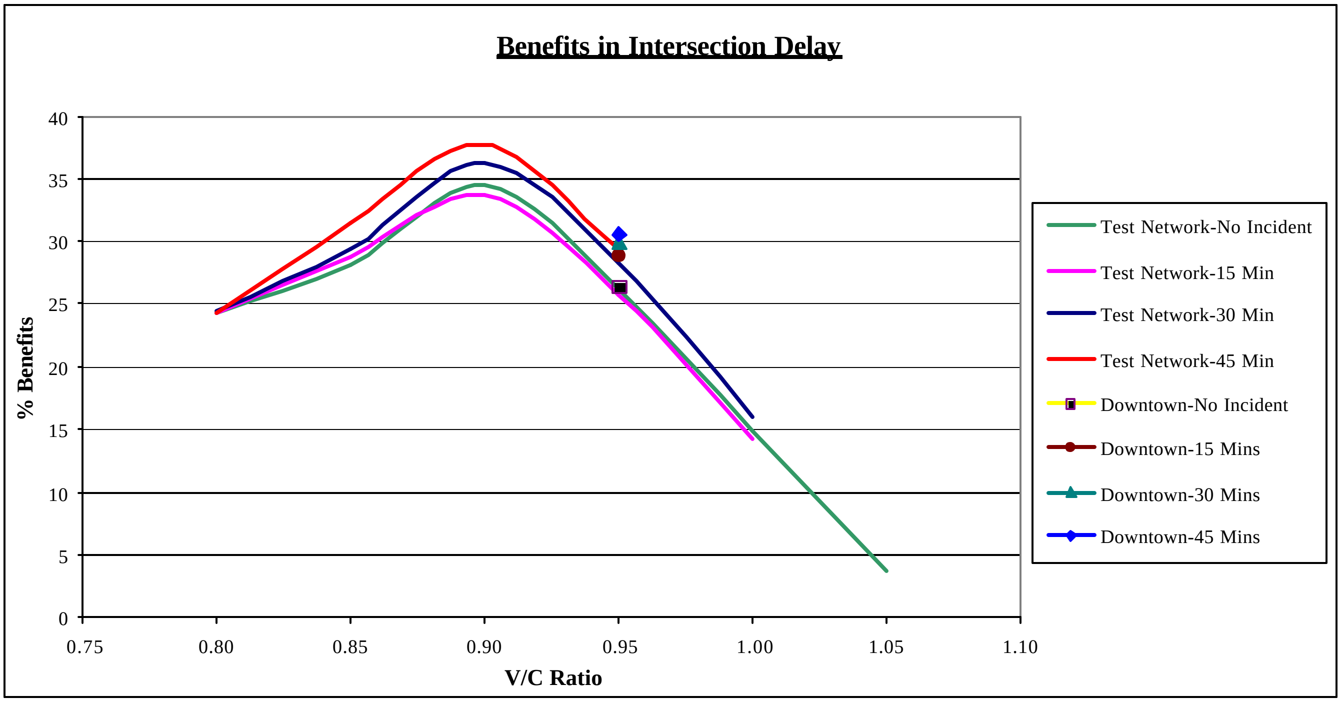
Analysis of SCOOT performance during Incident on Downtown network



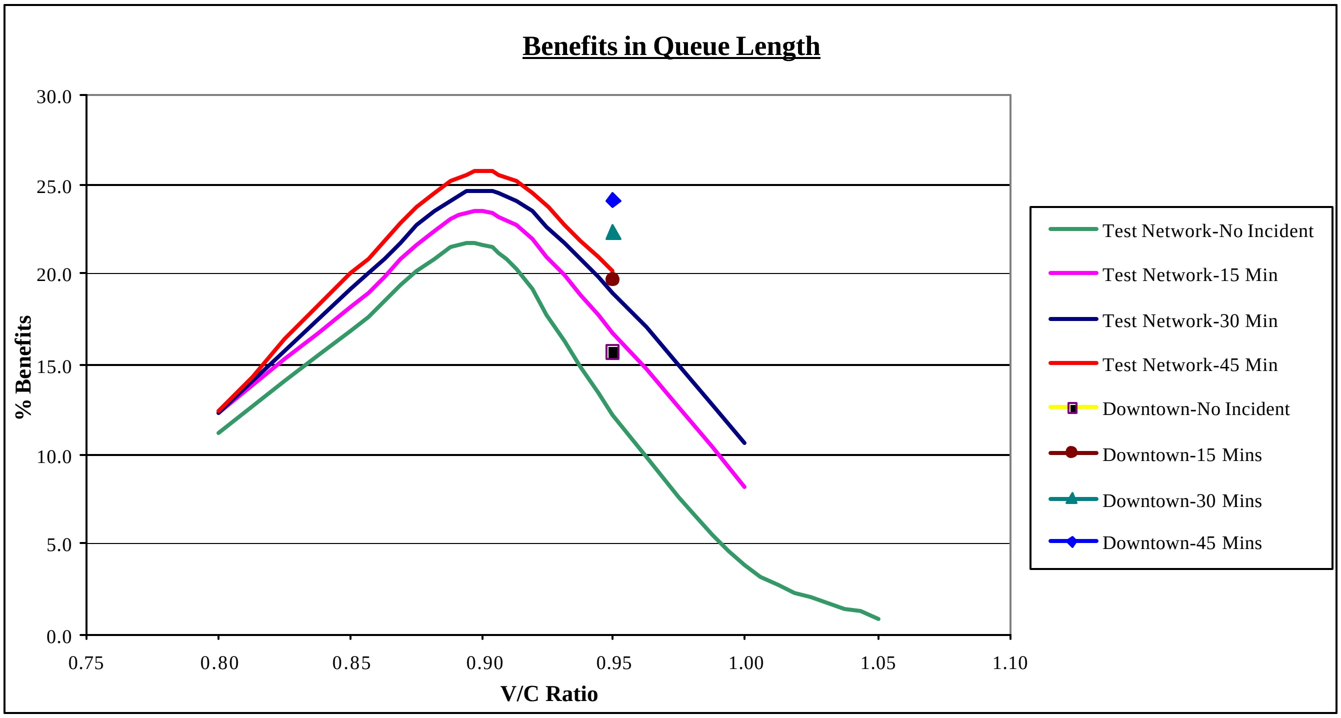
The network delay benefits of SCOOT over Synchro optimized FT on Salt Lake City downtown area network and test network.



The travel time benefits of SCOOT over Synchro optimized FT on Salt Lake City downtown area network and test network.



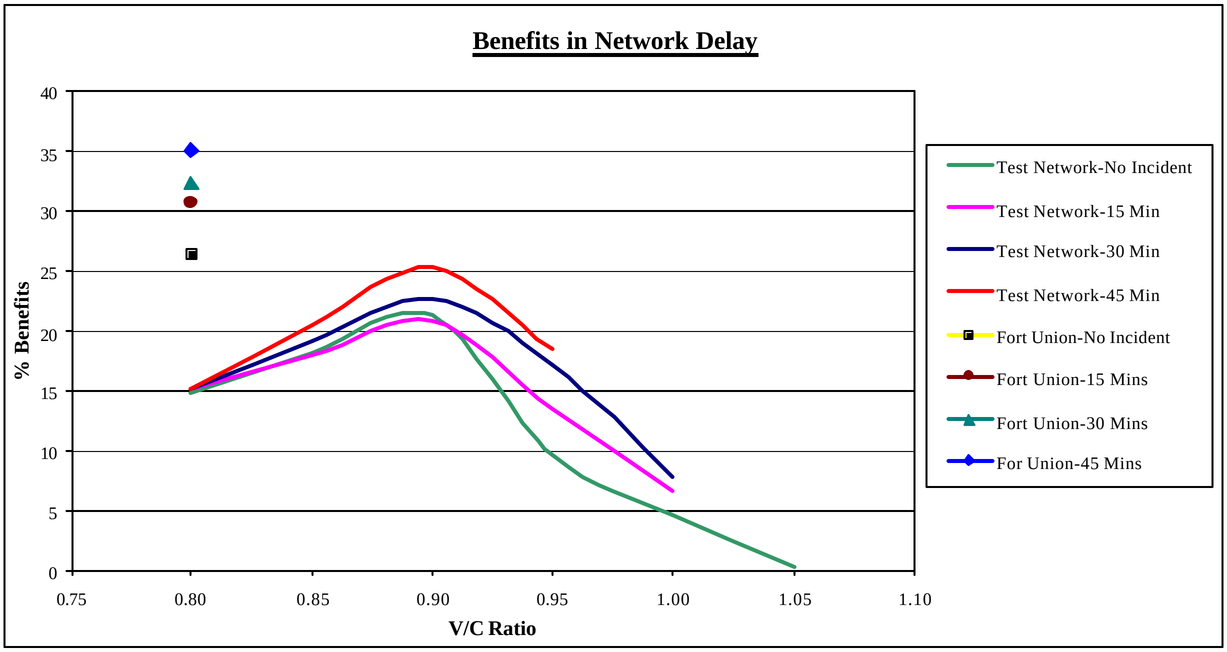
The intersection delay benefits of SCOOT over Synchro optimized FT on Salt Lake City downtown area network and test network.



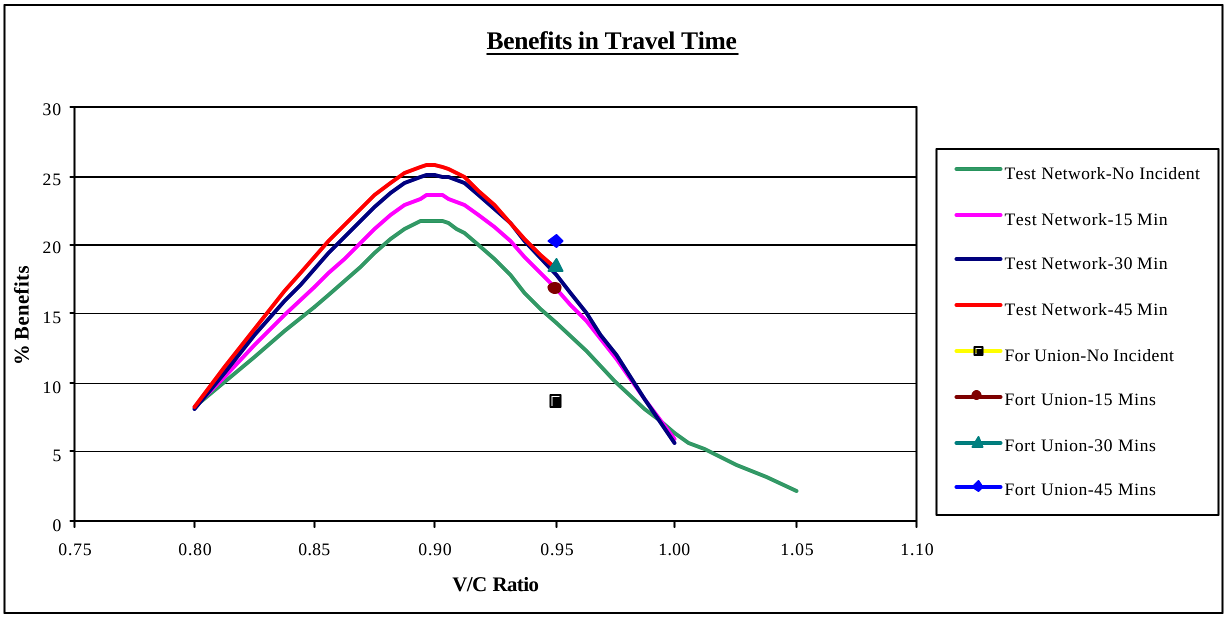
The queue length benefits of SCOOT over Synchro optimized FT on Salt Lake City downtown area network and test network.

APPENDIX C

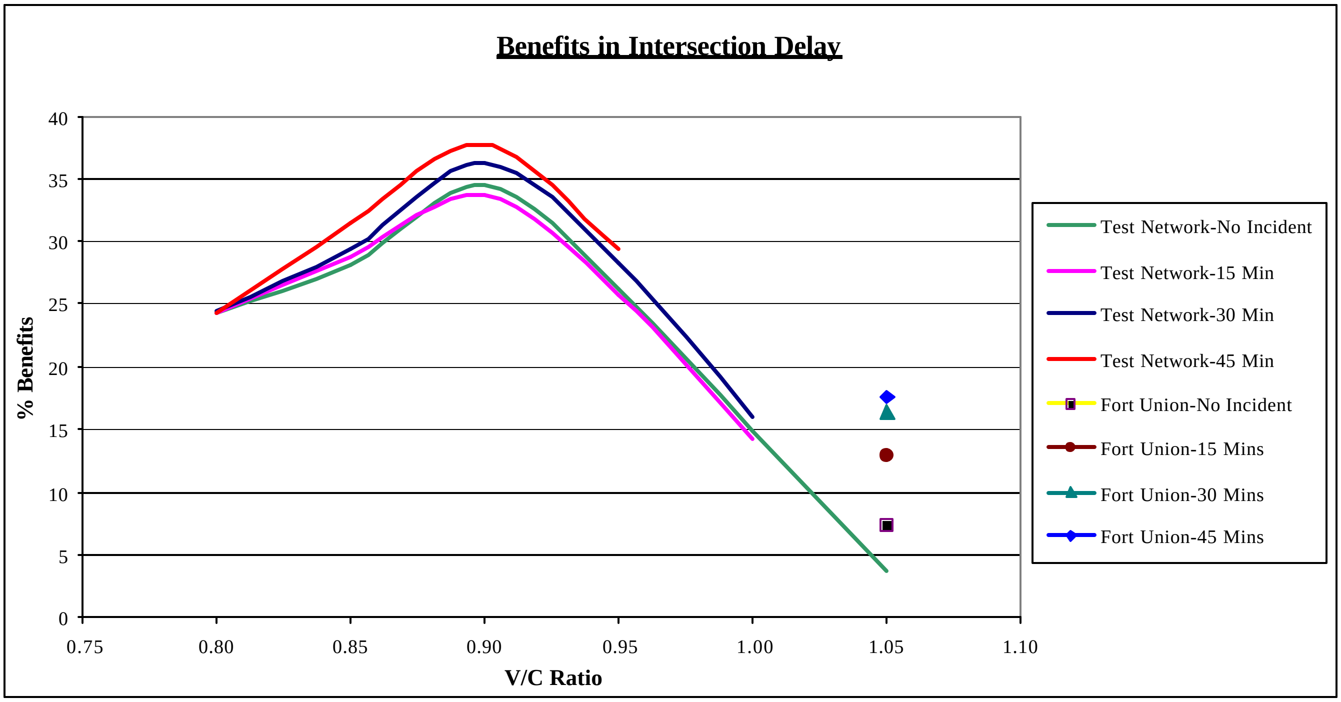
Analysis of SCOOT performance during Incident on Fort Union network



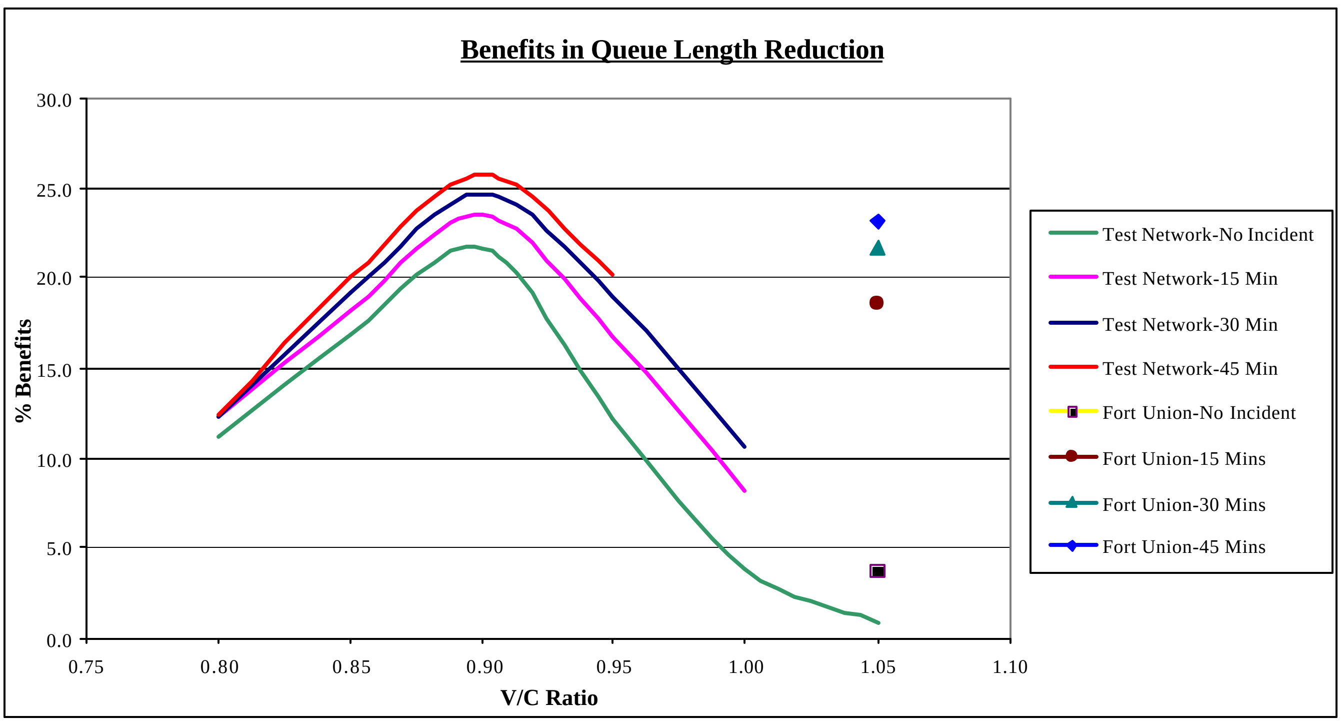
The network delay benefits of SCOOT over Synchro optimized FT on Fort Union area network and test network.



The travel time benefits of SCOOT over Synchro optimized FT on Fort Union area network and test network.



The intersection delay benefits of SCOOT over Synchro optimized FT on Fort Union area network and test network.



The queue length benefits of SCOOT over Synchro optimized FT on Fort Union area network and test network.

APPENDIX D

Analysis of E-Center Network and 3500 South

Benefits from Intersection Delay Reduction for E-Center Network

Intersection ID	2-hour Intersection Delay (veh-hrs)			% Benefit of SCOOT over Fixed-time (Synchro)	% Benefit of SCOOT over Fixed-time (TRANSYT)
	Fixed-time (Synchro)	Fixed-time (TRANSYT)	SCOOT		
1	16.4	19.3	16.2	1	16
2	24.4	24.2	17.0	30	30
3	31.1	31.0	19.7	37	36
4	30.5	30.0	25.8	15	14
5	57.6	48.6	32.0	45	34
6	63.6	92.6	74.9	-18	19
7	56.0	58.9	30.3	46	49
8	34.5	42.8	30.8	10	28
9	76.0	170.2	86.1	-13	49
Total	**390.1**	**517.6**	**332.8**	**15**	**36**

Benefits from Queue Length Reduction for E-Center Network

Intersection ID	Average Queue Length (feet)			% Benefit of SCOOT over Fixed-time (Synchro)	% Benefit of SCOOT over Fixed-time (TRANSYT)
	Fixed-time (Synchro)	Fixed-time (TRANSYT)	SCOOT		
1	940	980	920	2	6
2	740	800	720	3	10
3	880	840	640	27	24
4	880	920	860	2	7
5	2020	1780	1260	38	29
6	1220	1380	1300	-7	6
7	880	1240	740	16	40
8	820	980	900	-10	8
9	1180	2500	1280	-8	49
Total	**9560**	**11420**	**8620**	**10**	**25**

Benefits from Travel-time Reduction for E-Center Network

Corridor V/C	Average Travel Time (sec)						% Benefit of SCOOT over Fixed-time (Synchro)		% Benefit of SCOOT over Fixed-time (TRANSYT)	
	Fixed-time (Synchro)		Fixed-time (TRANSYT)		SCOOT					
Direction	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**
3100 S	231	224	227	228	219	205	5	6	4	10
3500 S	268	301	322	338	252	273	6	9	22	19
Average							**7**		**14**	

Benefits from Intersection Delay Reduction for 3500 South Corridor

Intersection ID	2-hour Intersection Delay (veh-hrs)			% Benefit of SCOOT over Fixed-time (Synchro)	% Benefit of SCOOT over Fixed-time (TRANSYT)
	Fixed-time (Synchro)	Fixed-time (TRANSYT)	SCOOT		
5	24.3	24.2	19.0	22	21
6	78.4	106.1	72.1	8	32
7	39.0	42.9	29.8	23	31
8	34.4	38.9	28.4	17	27
9	69.6	94.3	68.9	1	27
Total	**245.6**	**306.4**	**218.3**	**11**	**29**

Benefits from Intersection Queue Length for 3500 South Corridor

Intersection ID	Average Queue Length (feet)			% Benefit of SCOOT over Fixed-time (Synchro)	% Benefit of SCOOT over Fixed-time (TRANSYT)
	Fixed-time (Synchro)	Fixed-time (TRANSYT)	SCOOT		
5	1020	1020	1040	-2	-2
6	1440	1420	1280	11	10
7	860	1080	700	19	35
8	900	960	760	16	21
9	980	1080	920	6	15
Total	**5200**	**5560**	**4700**	**10**	**15**

Benefits from Travel-time Reduction for E-Center Network

Corridor V/C	Average Travel Time (sec)						% Benefit of SCOOT over Fixed-time (Synchro)		% Benefit of SCOOT over Fixed-time (TRANSYT)	
	Fixed-time (Synchro)		Fixed-time (TRANSYT)		SCOOT					
Direction	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**
3500 S	267	304	263	352	251	271	6	11	5	23
Average							**8**		**14**	

APPENDIX E

Statistical Analysis of Multiple SCOOT Runs

Benefits from Delay Reduction (veh-hrs) by Multiple SCOOT Runs

Node	**Synchro**	**SCOOT Iteration #**				
		1	**2**	**3**	**4**	**5**
1	33.0	27.7	27.9	27.3	27.3	27.1
2	30.0	21.2	23.2	21.2	24.7	22.4
3	56.0	37.6	39.4	38.9	38.7	37.0
4	16.3	17.4	18.0	18.5	14.7	14.2
5	26.7	25.6	25.7	25.9	22.6	22.5
6	10.6	10.4	10.7	11.2	10.6	10.3
7	49.2	29.5	32.2	32.6	31.8	32.3
8	31.3	27.7	28.5	23.5	24.1	25.0
9	19.4	12.8	14.4	13.9	14.0	13.3
10	19.9	15.1	15.3	14.1	13.9	14.9
11	29.5	15.4	17.9	17.5	19.5	17.7
12	34.7	22.3	23.1	23.2	28.1	25.4
13	27.1	17.4	18.4	19.0	17.7	15.4
14	75.1	51.7	50.9	54.8	52.8	52.5
15	12.0	6.4	6.7	6.7	6.9	6.7
16	28.4	22.1	22.0	22.3	22.3	21.9
17	41.0	24.5	27.6	26.7	24.8	23.7
18	23.6	28.0	29.4	26.4	26.7	26.2
19	81.7	87.8	84.4	86.0	84.5	84.4
20	103.8	51.5	48.2	49.8	51.0	61.0
21	8.0	9.3	9.2	9.3	10.2	8.9
22	6.8	8.7	7.8	8.9	9.3	9.3
23	5.2	6.6	6.0	6.5	7.0	7.1
24	10.1	8.1	8.2	8.5	8.9	9.2
25	15.4	19.9	19.9	20.5	18.7	19.8
26	20.0	18.6	16.9	18.0	18.1	18.0
27	13.8	14.6	14.1	13.1	13.8	13.3
28	7.5	6.7	6.3	6.8	6.4	6.3
Total	836.2	644.9	652.2	651.3	649.4	646.0
% Benefit over Synchro		22.9	22.0	22.1	22.3	22.7

The Students t test is used to analyze this data.

Total intersection delay for five SCOOT runs is 644.9, 652.2, 651.3, 649.4 and 646.0. The mean of the observations is X = 648.8 and the standard deviation is S = 3.21.

As number of observations n = 5, the $t_{.025}$ for 95% confidence level and 4 (= n-1) degrees of freedom is

$t_{.025}$ = 2.78

Therefore, µ = X $\underline{+}$ 2.78 (s/vn)

So, µ = 648.8 $\underline{+}$ 3.99; i.e. µ varies between 644.77 veh-hrs to 652.75 veh-hrs.

As the delay from a CORSIM file using Synchro fixed time plan is 836.2, it can be stated with 95% confidence that benefits from a SCOOT run will vary between 21.94% to 22.89%, or within $\underline{+}$ 0.475%. This is a reasonably small variation and therefore one SCOOT run per CORSIM input file is sufficient.

APPENDIX F

Statistical Analysis of Random Number Variation

Benefits from Delay Reduction (veh-hrs) by Multiple SCOOT Runs

	Delay (veh-hrs)									
Random Number	**7781**		**4231**		**4983**		**5859**		**5649**	
Node	**Sync***	**SC***	**Sync**	**SC**	**Sync**	**SC**	**Sync**	**SC**	**Sync**	**SC**
1	33.0	27.7	33.5	27.2	31.9	26.8	32.8	29.4	31.9	27.9
2	30.0	21.2	29.5	21.7	29.3	22.6	29.1	23.3	29.4	21.4
3	56.0	37.6	55.1	38.9	57.1	38.1	55.3	38.1	54.6	37.4
4	16.3	17.4	16.4	13.5	16.2	17.6	16.1	13.3	15.4	18.0
5	26.7	25.6	27.3	22.7	26.6	24.7	25.7	23.4	26.6	25.1
6	10.6	10.4	10.8	9.3	10.8	11.0	9.9	9.5	10.9	11.4
7	49.2	29.5	48.2	30.6	47.5	35.6	47.8	30.5	47.3	33.5
8	31.3	27.7	31.0	28.6	29.5	24.4	29.8	26.4	30.5	27.1
9	19.4	12.8	19.3	14.2	18.5	13.7	19.6	14.7	19.7	13.9
10	19.9	15.1	21.0	14.7	20.4	14.9	20.3	14.0	20.1	14.8
11	29.5	15.4	29.2	20.4	28.7	19.9	28.8	18.7	29.5	18.4
12	34.7	22.3	33.9	23.5	33.8	26.1	34.3	25.2	35.2	20.6
13	27.1	17.4	27.0	19.4	27.4	16.8	27.0	21.3	27.4	18.5
14	75.1	51.7	72.7	50.0	76.5	48.2	69.0	55.3	77.3	47.2
15	12.0	6.4	11.2	7.4	11.0	8.2	11.8	8.0	11.4	8.4
16	28.4	22.1	28.4	23.3	28.8	22.4	28.1	22.4	27.9	22.4
17	41.0	24.5	42.7	23.7	41.7	21.0	39.7	23.9	43.0	17.8
18	23.6	28.0	24.6	26.2	23.9	28.5	24.0	27.8	23.6	25.3
19	81.7	87.8	90.2	84.2	78.0	75.7	78.0	80.1	80.7	76.5
20	103.8	51.5	99.1	60.9	102.5	50.9	112.8	47.6	94.3	58.1
21	8.0	9.3	8.3	10.2	8.4	9.3	8.3	8.9	8.3	9.4
22	6.8	8.7	6.8	8.7	6.9	7.7	6.6	8.6	6.5	9.6
23	5.2	6.6	5.2	6.3	5.0	5.3	5.0	6.5	4.9	7.5
24	10.1	8.1	9.5	7.6	10.0	9.3	9.5	8.7	9.8	9.4
25	15.4	19.9	15.2	18.7	15.1	21.2	15.5	18.4	14.6	20.1
26	20.0	18.6	19.9	17.3	20.4	16.3	19.5	17.0	19.8	16.4
27	13.8	14.6	15.4	14.2	14.4	13.0	14.1	13.6	13.0	13.5
28	7.5	6.7	8.1	6.9	7.7	6.5	7.6	6.0	7.8	6.3
Total	**836.2**	**644.9**	**839.6**	**650.2**	**827.9**	**635.8**	**825.9**	**640.4**	**821.5**	**635.9**
% Benefit over Synchro	22.9		22.6		23.2		22.5		22.6	

*Sync = Synchro fixed-time plan; *SC = SCOOT control

The Students t test is used to analyze this data.

Percent benefits from SCOOT over Synchro fixed-time control for five random numbers runs are 22.9, 22.6, 23.2, 22.5, and 22.6. The mean of the observations is X = 22.8 and the standard deviation is S = 0.277.

As number of observations n = 5, the $t_{.025}$ for 95% confidence level and 4 (= n-1) degrees of freedom is $t_{.025} = 2.78$

Therefore, $\mu = X \pm 2.78 (s/vn)$

So, $\mu = 22.8 \pm 0.34$; i.e. μ varies between 22.46% to 23.14%.

It can therefore be stated with 95% confidence that benefits from a SCOOT over Synchro wth any random number will vary between 22.46% to 23.14%, or within ± 0.34%. This is a reasonably small variation and therefore one SCOOT run per CORSIM input file using default CORSIM random numbers is sufficient.

The performance of SCOOT on test, Salt Lake City downtown area, and Fort Union area networks, for all the incident scenarios, is given in the previous chapter. In this chapter, the results observed on the test network are compared with the observations on real-world network.

This chapter is subdivided into two sections. The first section compares the test network results with the results observed on the Salt Lake City downtown area network. The second section compares the test network results with the results observed on the Fort Union area network.