ASSESSMENT OF SURROGATE SAFETY BENEFITS OF AN ADAPTIVE TRAFFIC CONTROL SYSTEM

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ABSTRACT

When Adaptive Traffic Control Systems are evaluated their safety benefits are rarely investigated. This 'lack of interest' in safety performance may be attributed to two major factors: 1) field assessments of safety improvements are impractical (i.e. time consuming and costly), and 2) methods for obtaining safety metrics from microscopic simulation models are uncommon. While collecting and analyzing field safety metrics (e.g. crash rates) remains operationally and analytically challenging, new tools are becoming available to provide surrogate safety measures based on microscopic simulation program outputs. The framework of this study uses a microsimulation model connected to Sydney Coordinated Adaptive Traffic System (SCATS) to generate vehicular trajectories which are fed into a Surrogate Safety Assessment Model. Real-world data from two Utah state routes are collected to reflect crashes before and after the adaptive system was deployed in 2006. The crash data are analyzed and compared to relevant surrogate safety measures to detect potential correlations between the two data sets. Results show that SCATS generates fewer rear-end and total conflicts than traditional traffic control while traditional control generates fewer crossing and lane-changing conflicts. Field crashes have increased in the last few years likely as a consequence of more numerous road construction activities. Correlation indicators between field crashes and simulated conflicts are not very strong but follow trends reported by other studies.

Keywords: adaptive traffic control, safety surrogate measures, microsimulation, crash statistics.

INTRODUCTION

There is a long history of Adaptive Traffic Control System (ATCS) evaluations, both in field and microsimulation (Stevanovic, 2010). However, when performance of an ATCS is evaluated the safety benefits of its signal timings are rarely evaluated and documented (Sabra et al., 2010). This 'lack of interest' in the safety performance of an ATCS may be attributed to two major factors: 1) field assessments of safety improvements are impractical (i.e. time consuming, costly, and possibly lacking definitive results), and 2) methods for obtaining safety metrics from microscopic simulation models are still uncommon.

Field safety assessments of traffic signal designs are often inconclusive because relationships between safety metrics (such as crash rates) and 'controlled' variables are often relatively low, even when 'controlled variables' (such as weather, geometrical design of the roads, and presence of work zones) have much higher impact on traffic safety than signal controllers' timings. Due to these problems very few studies have addressed impact of safety on signal timings on arterial roads. And until recently, there was no widely-available tool to estimate potential conflicts associated with various signal timing designs. Breakthrough research was initiated by the Federal Highway Administration (FHWA) (Gettman and Head, 2003) which led to development of the Surrogate Safety Assessment Model (SSAM) - software that calculates surrogate safety metrics based on conflicts between vehicular trajectories from traffic simulation outputs.

Numerous ATCS evaluation studies (see (Stevanovic, 2010) for a list of studies) show that ATCSs usually outperform conventional traffic signal systems. However, performance measures delivered by these evaluation studies rarely go beyond common metrics of traffic efficiency (such as delays, stops or travel times) and almost never include safety metrics. On the other hand, it is important to investigate impact of ATCSs on safety aspects of traffic performance. Do dynamically changing signal timings from ATCSs, by responding to fluctuations in traffic demand, increase 'disturbances' in traffic flows and maybe negatively impact safety? Or do these dynamic signal timings make traffic flows smother with fewer stops and larger gaps enabling safer execution of conflicting movements? These are questions that have not been answered so far. Furthermore, most of these questions could not be answered through practical field data collections. Field crash data are difficult to correlate with signal timings due to noise from all other variables that may impact traffic safety. Thus, investigating the impact of ATCS signal timings on surrogate safety measures in a virtual and controlled environment, where all other variables are kept constant, is a valid approach. By comparing ATCS signal timings with those delivered by conventional Time-of-Day (TOD) offline-developed signal timing plans one can understand the marginal impact of changes in signal timings on number and potential severity of conflicts.

Scant effort has been made to investigate impact of ATCS on safety metrics. While there is a promising ongoing project (sponsored by FHWA) to incorporate safety assessment into an ATCS (Sabra et al., 2010) this project is still in its initial stage; and practical importance of its findings needs to be evaluated in the future. In addition, there has not been a single study that evaluates safety surrogate performance of a major ATCS in microsimulation. This study bridges that gap in existing knowledge by evaluating benefits of Sydney Coordinated Adaptive Traffic System (SCATS) over a conventional TOD system in terms of surrogate safety measures. The study also briefly analyzes field data and draw conclusions between findings from microsimulation and the field.

LITERATURE REVIEW

Field Safety Evaluation of Traffic Signals

When evaluating impacts of traffic signals on road safety, impacts of signal phasing (e.g. left-turn phasing design; Brehmer et al., 2003) or physical structure of traffic signals (e.g. position and reflectivity; Miska et al., 2002) on road safety are more commonly investigated than impact of signal timings. A major exception is intergreen time (amber + all-red), as there is abundance of research on how amber and all-red timings impact red-light running problems. For more information on this topic readers should see, among other studies, the following research: Jenkins, 1969; Stimpson et al., 1980; Wortman and Matthias, 1983; Finlay, 1984; Stein, 1986; Green, 2000; Bonneson and Zimmerman, 2004; and Zimmerman and Bonneson, 2005.

When attempting to estimate the direct impact of modifying signal timings (other than intergreen) on road safety, current field practice (Howard/Stein-Hudson Associates, Inc., 2010) is to apply one of the crash reduction factors reported by FHWA (FHWA, 2008). However, this approach is not very reliable because crash reduction rates may be based on a limited number of research studies. This is further documented by the Highway Safety Manual (AASHTO, 2010) which recognizes that the following crash-reduction treatments (related to signal timings but excluding any phasing, intergreen, or multimodal treatments) have *unknown* effect on crashes:

- Converting pre-timed phases to actuated phases
- Modifying cycle length
- Modifying phase durations
- Implementing split phases
- Implementing or improving signal coordination

Surrogate Safety Measures and Field Crash Statistics

History of correlating traffic conflicts with traffic accidents is relatively long (Zegeer and Deen, 1978) but unfortunately somewhat unsuccessful. While researchers have not been able to show that traffic conflicts (either from microsimulation or from the field) are strongly correlated to traffic accidents, three major arguments are used to justify continued interest in analyzing traffic conflicts as a mean to estimate traffic accidents:

- Although using traffic conflicts to estimate accidents is not significantly better than using past accident data, both approaches generally produce similar results (Migletz et al., 1985; Gettman et al., 2008).
- Conflicts should be used to estimate an expected rate of accidents, as opposed to predicting the actual number, because actual numbers can significantly vary by year (Migletz et al., 1985).
- Others, non-safety related variables (e.g. volume, speed, or occupancy) are not reliable estimators of accident rates either (Zhou or Sisiopiku, 1997).

Surrogate Safety Measures from Microscopic Simulation

Although there are many studies which investigated development of surrogate safety models to estimate number of crashes (see for example Son et al., 2008), this review focuses on those studies which address surrogate safety measures derived from microscopic simulation models.

One of first studies using a widely-available simulation model (for earlier studies see Cooper and Ferguson, 1976; Fazio and Rouphail, 1990; Kosonen and Ree, 2000) was conducted in 2002 by Drummond et al. when the authors found a high correlation ($0.54 \leq R^2 \leq 0.89$) between traffic efficiency performance measures (e.g. delays and stops) from simulation and field crash rates.

The following year saw a major breakthrough in research on surrogate safety measures based on microsimulation outputs. Gettman and Head (2003) developed functional requirements and algorithms for a software tool that analyzes surrogate measures generated by the simulation model. This research led to development of publicly-available SSAM software a few years later (Gettman et al., 2008). The surrogate measures generated by SSAM are based on the identification, classification, and evaluation of traffic conflicts that occur in the simulation model. An open-standard vehicle trajectory data format was designed and support for this format has been added as an output option by major simulation software vendors/developers.

Almost simultaneously with FHWA research on SSAM, a group of researchers from École Polytechnique Fédérale de Lausanne in Switzerland developed their own surrogate safety measure based on microsimulation outputs (Torday et al., 2003). Unlike SSAM, this measure reported only rear-end conflicts and was applied in a ramp-metering case study.

Several other studies followed with their own developments of surrogate safety measures or proposed modifications to the existing ones. Klunder et al. (2006) proposed development of a better framework for generating safety performance measures based on the Multi-Agent Real-time Simulator (MARS) interfaced with Quadstone Paramics microsimulation software. Ozbay et al. (2008) emphasized a need for well-calibrated and validated microsimulation models from which safety surrogate measures are collected. They developed a new crash index and modified an existing one, and proved that both indices match field data both temporally and spatially. Tarko et al. (2009) wrote a white paper to clarify concepts and definitions of surrogate safety measures. They also summarized past research, offered new ideas, and identified future research directions.

Safety Evaluation of Adaptive Traffic Control Systems

A literature review on safety evaluations of ATCSs does not reveal many studies. Moore and Lowrie (1976) investigated impact of traffic signal coordination on the number of traffic accidents in the field. They compared numbers of accidents from areas with and without coordinated signals and estimated a 23% reduction in number of accidents following traffic signal coordination. These findings were further utilized by Bastable (1980) to calculate economic and social impacts of reduction in accidents following a deployment of SCATS in Sydney.

Anzek et al. (2005) investigated the impact of converting operations at a signalized intersection from pre-timed phases to some sort of adaptive traffic control. Although authors introduced a feedback mechanism which changes phase durations in (near) real-time fashion, it seems that this sort of adaptive control was more similar to vehicle-actuated control (as used in the US) than to fully adaptive traffic control. The authors observed a 35% reduction in number of crashes after the conversion took place. However, the analysis was based on a relatively small sample size (data for one year before and one year after) and there was no indication whether observed rate of improvement differed from normal year-to-year variations in accident frequency. Similar findings (with smaller improvements of ~15%) were observed by others

(Bamfo and Hauer, 1997) when right-angle accidents were analyzed at signalized intersections with vehicle-actuated phases as opposed to fixed-time phases.

Zimmerman and Bonneson (2005), from Texas Transportation Institute, developed and evaluated the Detection Control System (DCS). This system detects the type of vehicle (e.g. heavy vehicle or passenger car) approaching an intersection and modifies the clearance time of the service phase appropriately to reduce the occurrence of large trucks caught in the dilemma zone. Although this system adaptively changes clearance times for heavy trucks, the system can hardly be considered a full ATCS which is known to modify multiple signal timing parameters (e.g. cycle length, offsets, and phase splits) on demand. Nevertheless, the DCS showed a significant reduction (~ 80%) in red-light running of heavy trucks without negatively affecting traffic efficiency.

Barcelo et al. (2003) investigated how a custom-built adaptive traffic control strategy can improve safety conditions in a major tunnel at the France-Spain border in Europe. Although authors did not use any surrogate safety measure (they used a control strategy to alternate platoons of heavy trucks entering opposite sides of the tunnel) the findings showed that adaptive control is a better option than fixed-time control.

Sabra et al. (2010) started a study, sponsored by FHWA, to incorporate surrogate safety measures into an ATCS (ACS Lite). The first phase of this effort was foundational because it provided a better understanding of how individual signal timing parameters (e.g. cycle length, offset, and splits) affect surrogate safety measures delivered by SSAM. However, the second phase, which is supposed to incorporate safety aspects into ATCS operations, is yet to be completed.

Finally, the most recent research on safety evaluations of an ATCS represents an effort by Midenet at al. (2011) to investigate exposure to lateral collisions at signalized intersections for two traffic control strategies. Authors compared exposure captured through video recordings from an intersection operating under both an adaptive real-time strategy called CRONOS (ContRol Of Networks by Optimization of Switchovers) and a time-plan strategy to vehicle-actuated ranges. The results showed that CRONOS reduced exposure to lateral collisions by roughly 5 min/h.

Summary of Past Research

Research studies do not present surrogate safety measures as reliable estimators of real-world crashes but they are still considered valid measures with a lot of potential for improvement. Available studies on surrogate safety measures from simulation modeling show the continued interest from research community. Except for a recent FHWA report (Sabra et al. 2010) there are practically no studies which address impact of (non-intergreen) signal timings on surrogate safety measures. There are no studies which show how major ATCSs perform in terms of safety, either in microsimulation or in the field.

METHODOLOGY

Methodology of this study, which is shown in Figure 1, follows a traditional way to evaluate performance measures from two operational designs in microsimulation environment. A microsimulation model was built, based on extensive field data collection, and then calibrated and validated. Two types of traffic control systems, SCATS and conventional TOD control, are modeled to closely resemble their field counterparts. Uncommon for this type of study, several procedures were developed to replicate variability of traffic flows observed in the field during a week in September of 2007. The reasoning behind this additional task was to overcome lack of simulation's ability to replicate variability of field traffic flows and expose two traffic control regimes to field-like traffic conditions in the virtual environment. After numerous simulations were executed in VISSIM, vehicular trajectories were exported to SSAM and processed to calculate various surrogate safety measures. Results of the SSAM analysis were analyzed and statistically tested. Finally, findings from field crash statistics were reported and their similarity to simulation conflicts were briefly analyzed and discussed.

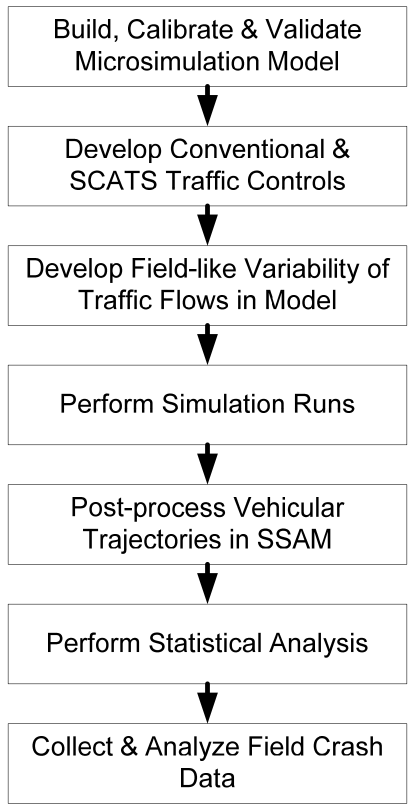


Figure 1 Workflow diagram

Microsimulation Model of Signalized Arterials in Park City

Park City Arterial Network

The Park City road network shown in Figure 2 consists of two suburban arterials, state routes (SR) 224 and 248, and many cross streets. SR 224 is a 5-lane major arterial while SR 248 is a 3-lane minor arterial. Both arterials have a median left-turn lane. Posted speed limits on SR 224 range from 55 mph along sparse sections with widely spaced intersections to 35 mph in the downtown area. Speed limits along SR 248 are 35 mph in the downtown area to 50 mph as the road leaves the network. Recent traffic counts have shown that SR 224 and SR 248 carry around 30,000 and 16,000 vehicles per day, respectively. SR 224 is the primary route for recreational traffic from Salt Lake City and other areas to ski resorts and recreational areas in Park City, and serves as a connector between Interstate 80 and U.S. Route 40. The network can be further divided into three distinct parts on the basis of prevailing traffic conditions:

- Kimball Junction is a single point urban interchange for SR 224 and I-80 followed by neighboring signalized intersections (Landmark Drive and Olympic Park). This area hosts many local businesses generating work-related and shopping traffic. It has the highest traffic demand throughout the day with Level of Service (LOS) C at the three intersections during the PM peak. The close proximity of the intersections dictates the need for coordination.
- Bobsled Drive, Bear Hollow, Sun Peak Drive, Canyons Drive, Payday Drive, and Thaynes Canyon comprise six intersections in the middle of the network and at the beginning of the downtown area providing access to residential and recreational areas. Intersections in this area have LOS A or B during the PM peak. Spacing between intersections allows some signals to run uncoordinated.
- Park Avenue and SR 248, Park Avenue and Deer Valley, Deer Valley and Bonanza Drive, Bonanza Drive and SR 248, and SR 248 and Comstock Drive are five intersections that form a small gyratory system providing circulation for traffic to access cultural and historical downtown Park City. The LOS for these intersections is B-A during the PM peak. Spacing warrants coordination between these intersections, but it is not mandatory because traffic flows can be very low.

In fall 2005, the Utah Department of Transportation (UDOT) installed and fine-tuned SCATS on all (then 12) signalized intersections in Park City. However, soon after initial SCATS was deployed two new intersections (at Bobsled Dr and Sun Peak Dr) were signalized and added to the existing system of 12 signalized intersections. Also, one of the existing signalized intersections (at Canyons Dr) was redesigned from a three-leg into a four-leg intersection. The three modified intersections were eventually brought under the SCATS umbrella and fine-tuned within a year and a half since the start of the SCATS installation.

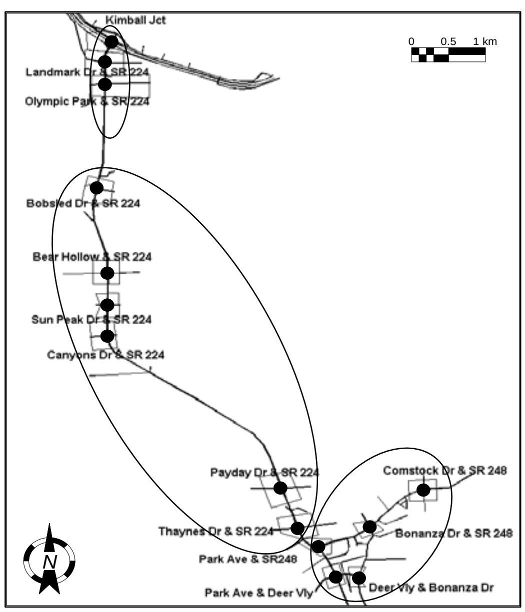


Figure 2 Signalized Intersections in Park City, Utah

Model Building & Data Collection

A VISSIM model of Park City was built based on extensive data that was collected in the field before SCATS was installed. PTV software (VISSIM) was selected as one of the few simulation platforms that interfaces both SCATS and SSAM. Data collected (under fair weather and dry pavement conditions) in a 3-week campaign included: geometry surveys for each intersection, stopped delays, saturation flow rates, turning movement counts, corridor travel times along the route (11.8 km) covering all signalized intersections, spot speeds, and vehicle classification. Data covered AM and PM peaks as well as mid-day traffic conditions. A detailed explanation of the data collection and methods used is provided elsewhere (Kergaye et al., 2010).

Calibration and Validation of the Model

The Park City VISSIM model was calibrated based on driving behavior captured through multiple traffic metrics collected in the field. A calibration process was performed manually through adjustments to the following elements of the VISSIM model:

- VISSIM's speed distributions and desired speed decisions were based on speed limits, spot speed data from the field, and preliminary travel time runs on segments of the network;
- Saturation flows at links approaching intersections in VISSIM were adjusted to represent saturation flow values collected in the field. Saturation flows in VISSIM are not explicitly (and accurately) defined but they can be tuned by adjusting relevant driving behavior parameters such as the additive and multiplicative parts of desired safety distances (PTV, 2010).
- VISSIM's routing decisions reflect traffic counts collected in the field. VISSIM's traffic inputs were adjusted to ensure that traffic demand approaching each intersection is high enough to generate traffic counts in VISSIM which match the traffic counts in the field.

The model was validated through a comparison of modeled (10 randomly seeded runs) and field travel times, measured along segments between signalized intersections. Figure 3 shows results of the validation process.

Modeling Traffic Control in VISSIM

Conventional TOD Traffic Control

Conventional TOD traffic control in Park City, before SCATS was deployed, was predominantly actuated-coordinated with two intersections that run an uncoordinated regime (SR 248 intersecting Bonanza Drive and Comstock Drive). The first three intersections in the Kimball Junction area were running on 128-second cycles. The other intersections all ran on 106-second cycles with exception of Deer Valley and Bonanza Drive which was double cycling (53 sec.). Conventional TOD signal timing data for the original 12 intersections were provided by UDOT in two forms: SYNCHRO files and detailed layouts of detectors and signal controller outputs for each intersection. Signal timings from the 12 field controllers were compared with those from the SYNCHRO files resulting in a few discrepancy corrections. Three modified intersections (Bobsled, Sun Peak, and Canyons) warranted development of new signal timings to consistently compare their performances with SCATS. New signal timings for these intersections were developed (in SYNCHRO) in such a way that traffic performance is optimized while keeping signal timings from the rest of the network unaltered. Finally, all signal timings from SYNCHRO were exported to VISSIM's RBC (Ring-Barrier Controller) platform and inspected manually for inconsistencies.

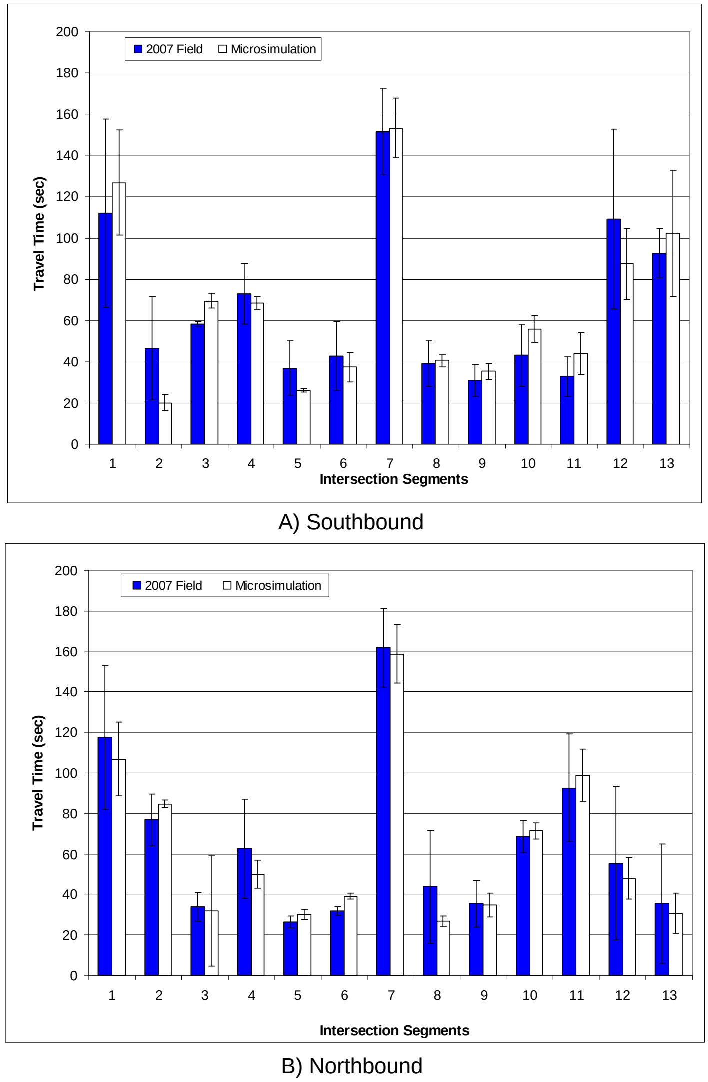


Figure 3 Results of validation process: travel times between intersections

SCATS Adaptive Traffic Control

SCATS is a two-level hierarchical ATCS developed in Australia in the 1970s by the Road and Traffic Authority (RTA) of New South Wales, Australia (Lowrie, 1982; Luk, Sims, and Lowrie, 1982). SCATS uses information from vehicle detectors, located in each lane immediately in advance of the stop line, to adjust signal timings in response to variations in traffic demand and system capacity. At a simple level, SCATS can be considered a feedback system that adjusts signal timings on the basis of changes in traffic flows from previous cycles. The SCATS strategy assumes that higher cycle lengths mean greater intersection capacity. This strategy advocates splits proportional to approach demand and longer offsets for increased volumes (and slower traffic flows). For more information about SCATS logic and features, readers are referred to the literature (Lowrie, 1992).

The SCATS traffic control was modeled in VISSIM through SCATSIM to represent an exact copy of the field-deployed SCATS in Park City. SCATSIM is a version of SCATS that is used to model SCATS operations in a microsimulation environment. SCATSIM (as well as SCATS) is developed and maintained by RTA of New South Wales. Florida Atlantic University (FAU) enjoys the privilege of a SCATSIM license, which was used in these experiments.

The SCATS-microsimulator (in this case VISSIM) connection is established through a combined Software-in-the-Loop (SIL) and Emulation-in-the-Loop (EIL) combination. The central SCATS server, SCATS region, and SCATS Access (version V6.7.2.0) were installed on the same computer running VISSIM. The interface between SCATS and VISSIM was established through an EIL application (WinTraff). The same concept was documented in earlier studies (Wilson et al., 2006; Kergaye et al., 2010).

The actual SCATS configuration that runs in the field was copied and deployed in SCATSIM at FAU. Adjustments and fine-tuning of SCATS were performed by SCATS experts from TransCore over eighteen months following system installation. Detectors and other geometric conditions in the VISSIM model were adjusted to match those in the field closely. Use of the fine-tuned SCATS signal control from the field eliminated a need for extensive and lengthy fine-tuning in the lab. Figure 4 shows screen shots from VISSIM and SCATS depicting how vehicles activate detectors as they approach an intersection.

Modeling Variability of Field Traffic Flows

Microsimulation programs have improved significantly over the last few decades. However, these tools are predominantly used to comparatively evaluate (relative to each other) performance measures of various operational scenarios. Their ability to accurately resemble field traffic conditions is still questioned though. Of special concern is the inability of microsimulation tools to replicate variability of field traffic conditions. For example, although VISSIM is known as one of the tools with the best capability to fluctuate traffic load in its network, it was shown that its internal traffic generators could not resemble traffic variability observed in the field (Stevanovic and Kergaye, 2010).

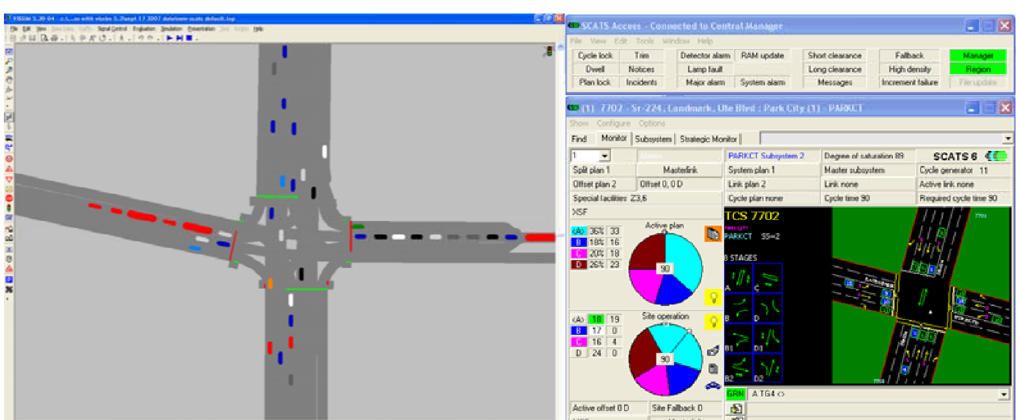


Figure 4 Vehicular activations of detectors in VISSIM (left) and SCATS (right)

It was the authors' particular interest to investigate performance of various traffic control regimes in fluctuating traffic demand. ATCSs are known as systems which should be able to respond to fluctuations in traffic demand, so it was an imperative to capture their behavior in such a varying traffic flow environment. In order to do so, authors developed a set of procedures which manipulated outputs from the field SCATS in Park City and used those outputs to recreate traffic in the virtual VISSIM environment. Although details about these procedures are documented elsewhere (Stevanovic and Kergaye, 2010) here are major steps that depict the process:

- Field 15-minute traffic counts were obtained from the SCATS Strategic Monitor (SM) outputs (not available for right turns)
- Hourly traffic counts were obtained from two other sources: manual data collection (available for all turns) and automatic traffic records (limited to few turns)
- All of the traffic counts were imported into a spreadsheet which reflected the structure of Park City network's traffic input points and turning movements
- Traffic counts from various sources were checked for consistency and combined to create a complete set of hourly turning movement counts
- A traffic flow balancing algorithm was applied (coded in spreadsheet form) to preserve conservation of flows in the network
- Resulting volumes were exported as a set of traffic inputs and routing decisions (elements of VISSIM network) into VISSIM's files
- The entire process was repeated for PM peak hours for five consecutive days representing a week of traffic variation between September 17th and September 21st, 2007.

This process represented an effort to recreate field traffic volumes in the microsimulation model to closely resemble variability of field traffic flows. Figure 5 shows the correlation between modeled traffic flows (VISSIM) and those from the field (SCATS outputs), for a pair of turning movements. Similar correlations were achieved for most of the other turning movements with exceptions for right turns used for volume balancing.

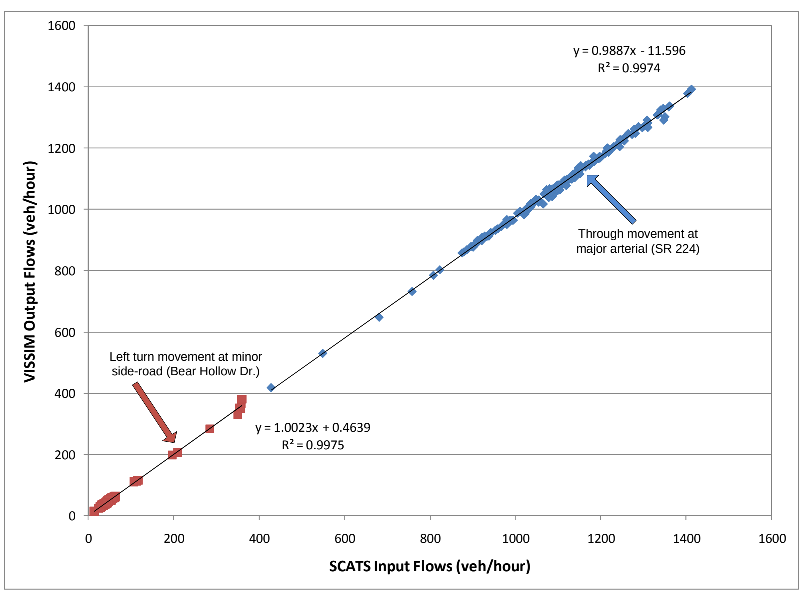


Figure 5 Comparison of Field (SCATS) and Simulated Traffic Volumes

Simulation Runs

Simulations of SCATS and coordinated-actuated traffic control regimes were executed in VISSIM's version 5.3 through 10 randomly seeded simulation runs for each of the five days representing field traffic flows. Each simulation run was one hour and 15 minutes long, which corresponds to the PM peak hour with additional 15 minutes for simulation warm-up. Each of the 100 (5 days x 10 runs x 2 scenarios) simulation runs reported conventional performance measures (delay, stops, etc.) as well as trajectory files for all vehicles in the format suited for further processing in SSAM (*.trj files).

Post-Processing Simulation Outputs in SSAM

After VISSIM generates files (*.trj extension) with individual trajectory data for each vehicle, SSAM calculates surrogate measures of safety corresponding to each vehicle-to-vehicle interaction. Based on positions of individual vehicles during the course of simulation, SSAM filters those vehicular interactions to satisfy user-defined conflict criteria, and reports them as vehicular conflicts. Definition of SSAM's surrogate measures and workflow are presented in the literature (Gettman and Head, 2003). Authors' focus in this paper is mainly on number and type of conflicts reported by SSAM.

Conflict type is determined based on angle between headings of two vehicles causing the conflict as documented in the Surrogate Safety Measure report (Gettman and Head, 2003),. Based on the angle SSAM recognizes three types of conflicts: rear-end, lane-change, or crossing movement. The conflict type is classified as a rear-end conflict if ||ConflictAngle|| < 30 degrees, a crossing conflict if ||ConflictAngle|| > 85 degrees, or otherwise a lane-change conflict (Gettman and Head, 2003). Degree values for determination of these conflict types are user configurable. Authors used default values for all conflict thresholds (including TTC of 1.5 sec and PET of 5 sec) with exception of crossing angle (θ_2) which was selected to be 85^o (default SSAM value is 80^o). Once SSAM processed trajectory files from VISSIM simulation runs, data were exported to spreadsheets for further analysis.

Statistical Analysis of Safety Benefits from ATCS

SSAM raw data and summary statistics were exported to MS Excel spreadsheets where further statistical analysis was performed. Similarly, VISSIM outputs depicting mostly efficiency performance measures of the two traffic control regimes, were exported in the spreadsheets. For each of the performance measures (safety from SSAM and efficiency from VISSIM) a statistical test was performed to investigate similarity of the counterpart simulation runs for SCATS and Conventional TOD control. Paired T-tests (for the same random number seeds) were used to test the null hypothesis that means of performance measures from SCATS and Conventional TOD Control runs are equal, with 95% confidence level.

Collection and Analysis of Crash Data from the Field

Field crash data were collected from UDOT's database (called Safety Management System). Entries into this database are provided by the Utah Department of Public Safety (law enforcement) via electronic or hard copy format. The collected data is over 85% compliant with Model Minimum Uniform Crash Criteria, which represents a national guideline. The form was revised in 2006, although the data used in this study prior to 2006 was not affected by the change.

Three types of crashes were retrieved for analysis with traffic conflicts from simulation. These were coded by manner of collision 1, 2, and 4, and respectively represented Angle crashes, Front to rear (F-R) crashes, and Sideswipe (S-S) (same direction) crashes. Obviously, these three types were considered the best field crash matches to crossing, rear-end, and lane-changing conflicts reported by SSAM, respectively. Although these matches between conflicts and crashes are not perfect, they represent the best assumptions considering availability and classifications of both data types.

Out of 14 intersections that were eventually operating under SCATS, after it was deployed, 4 intersections were eliminated from the data analysis because of changes to the intersections or surrounding areas after the SCATS system was installed. The traffic signals at two of these locations (Bobsled Dr and Sun Peak) were installed after the SCATS system. The traffic signal for Canyons Drive was moved and changed from a T-intersection to a 4-leg intersection. Additionally, the intersection on SR-224 at Bear Hollow was excluded from data analysis because it is surrounded by two of the new traffic signals.

Automatic Traffic Recorders provided Annual Average Daily Traffic along each route at two specific locations: SR 224 at milepost 8.92 (or 0.1 mile north of the Canyons intersection), and SR 248 at milepost 2.561 (or 0.5 miles west of SR 40). Due to construction, traffic counts along SR 224 for the first two months of 2007 were not recorded. In this case the remaining 10 months were used as representative data.

RESULTS AND DISCUSSION

Simulation Experiments

Table 1 shows various metrics collected from simulation and SSAM outputs for the two traffic control regimes. Table 1 is vertically divided into three parts to consecutively show information about vehicular conflicts (total and by type), other SSAM metrics, and conventional performance measures of traffic efficiency such as delay and number of stops, etc.

Results for vehicular conflicts show that SCATS reduced the total number of conflicts by more than 11%, a reduction that can be totally attributed to a reduction (of 13%) in number of rear-end conflicts. However, SCATS increased the number of crossing and lane-changing conflicts by 28% and 5%, respectively. These results are expected considering operational changes that were made by SCATS deployment. Most of these differences in conflicts pertain to the area of Kimball junction – the busiest in the network. SCATS contributes to the differences in two ways, each of which can be attributed to one of the three conflict types:

1. SCATS' limit for maximum cycle length in peak hours is 150 seconds versus 128 seconds from Conventional TOD control. Increased cycle length (whose major portion is allocated to main-road traffic) facilitate better progression between intersections in the Kimball Junction area (Table 1 shows that the number of stops is reduced by 14%). Better arterial progression and fewer stops cause fewer rear-end conflicts. These results confirm findings from a recent FHWA report that correlates longer cycle lengths to fewer rear-end conflicts (Sabra et al., 2010).
2. In order to better facilitate traffic progression on the main-road, side-street protected left turn green times were slightly reduced when SCATS was deployed. This modification

caused fewer side-street left turns during the protected phase, which consequently increase the number of left-turning vehicles waiting for a gap from opposing traffic during the permitted left-turn phase. Although this strategy does not significantly impact efficiency of left-turn traffic it seems that the number of crossing conflicts is increased. One should note here that others reported that crossing conflicts are the least reliable of all SSAM estimates (Gettman et al., 2008).

Increase in number of lane-changing conflicts cannot be firmly attributed to any obvious change in signal timings. A potential reason for this increase may be that vehicles waiting longer in queue (due to longer cycle lengths) may be prone to conduct more lane-changing maneuvers. When it comes to other SSAM metrics, the high number of observations (on average more than 11,000 conflicts per experiment) justifies statistically different results between SCATS and Conventional TOD control even in cases where differences are practically negligible.

Table 1 Performance measures of SCATS and Conventional TOD traffic control

	Conventional TOD Control		SCATS Control		
	Mean	Standard Deviation	Mean	Standard Deviation	Relative Difference
Conflicts					
Total number of conflicts	12422.3	3422.18	10972.6*	1517.03	-11.67%
Crossing conflicts	86.86	10.31	111.48*	19.15	28.34%
Rear-end conflicts	11462	3269.42	9943.88*	1439.5	-13.24%
Lane-changing conflicts	873.42	174.49	917.24*	88.16	5.02%
Other SSAM Metrics					
TTC	1.05	0.46	1.03*	0.47	-1.90%
PET	2.6	1.2	2.53*	1.24	-2.69%
MaxS	5.51	3.31	5.60*	3.36	1.63%
DeltaS	3.53	2.12	3.56*	2.18	0.85%
DR	-3.46	2.88	-3.39*	2.89	-2.02%
MaxD	-5.3	2.42	-5.18*	2.51	-2.26%
MaxDeltaV	1.85	1.17	1.87*	1.21	1.08%
VISSIM Metrics					
Total Delay (hours)	264.44	29.27	252.86*	18.24	-4.38%
Number of stops	54533.9	16119.49	46899.48*	6959.21	-14.00%
Throughput (vehicles/hour)	11096.46	82.98	11080.84	88.31	-0.14%
Total stopped delay (hours)	134.97	14.48	135.19	12.22	0.16%
Average speed (miles/hour)	26.9	0.74	27.211*	0.49	1.16%
Total travel time (hours)	968.34	30.73	955.19*	19.11	-1.36%
Number of simulation runs	50		50		

* - statistically different (at 95% confidence level) from corresponding Conventional TOD control value

Where (Gettman and Head, 2003):

TTC - the minimum time-to-collision value observed during the conflict.
PET - the minimum post-encroachment time observed during the conflict.
MaxS - the maximum speed of either vehicle throughout the conflict.
DeltaS - the difference in vehicle speeds as observed at tMinTTC.
DR - the initial deceleration rate of the second vehicle, recorded as the instantaneous acceleration rate.
MaxD - the maximum deceleration of the second vehicle.
MaxDeltaV is the maximum DeltaV value of either vehicle in the conflict.

Finally, when two traffic control regimes are compared for their efficiency SCATS outperforms Conventional TOD control in almost every aspect. SCATS reduces total delays by ~ 4% whereas number of stops is reduced by 14%. These results correspond to a range of performance measures that were collected in the field (Martin and Stevanovic, 2007). Finally, results for throughputs show that neither SCATS nor Conventional TOD control 'process' more vehicles than the other regime, which proves that efficiency improvements from SCATS are not a result of constraining vehicular access into the network. Again, due to the relatively large sample size, results of statistical tests show significant differences even for those metrics whose differences are smaller than 2% (average speed & total travel time).

Field Crash Data

Table 2 shows crash frequency for each year based on various crash types. Data presented in Table 2 does not include any other types of crashes except the three which were mentioned above. Traffic volume data (AADTs) show that traffic increased about 2,000 vehicles per day on SR 248 in the last 4-5 years. On the other hand, there is no obvious increase in traffic on SR 224.

When looking at the average number of crashes per year the data shows that the number of crashes increased after 2006. However, due to a smaller sample size it is difficult to extract reliable indicators of dispersion for these crash numbers. Standard deviations from these limited samples show that difference in number of crashes (before and after the ATCS deployment) falls within 1-2 standard deviations.

It is interesting to observe that the highest number of crashes both on SR 224 and SR 248 occurred in 2007 and 2008, most likely due to the significant road construction activities in the area. Before 2007, a year with the highest number of crashes on SR 224 (and the second highest on SR 248) was 2002 – most likely due to traffic before and during the Winter Olympic Games (Park City was one of the major venues). Overall, in spite of the fact that the number of crashes increased after SCATS deployment, authors would be very reluctant to associate this increase in crashes with deployment of an ATCS. More analysis is needed to find out what could be potential reasons for the increase in crash frequency after 2006.

Table 2 Field crash data and AADTs before and after SCATS deployment in Park City, UT

	SR 248					**SR 224**				
Before	Total	Angle	F-R	S-S	AADT	Total	Angle	F-R	S-S	AADT
2002	*38*	17	17	4	12,254	*67*	13	43	11	28,612
2003	*29*	13	15	1	12,349	*42*	6	29	7	27,787
2004	*35*	15	17	3	13,338	*50*	6	35	9	29,176
2005	*40*	19	18	3	13,827	*64*	17	40	7	30,499
< May 2006	*15*	9	4	2	15,023	*13*	8	4	1	23,545
Total	*157*	*73*	*71*	*13*	*66,791*	*236*	*50*	*151*	*35*	*139,619*
Average	*36*	*17*	*16*	*3*	*13,358*	*54*	*12*	*35*	*8*	*27,924*
After	Total	1	2	4	AADT	Total	1	2	4	AADT
>Jul 2006	*19*	9	8	2	15,023	*31*	13	14	4	23,545
2007	*56*	29	25	2	15,919	*89*	31	50	8	29,525
2008	*50*	27	20	3	15,209	*75*	36	36	3	29,253
< Nov 2009	*5*	1	4	0	14,655	*38*	17	20	1	27,582
Total	*130*	*66*	*57*	*7*	*60,806*	*233*	*97*	*120*	*16*	*109,905*
Average	*39*	*20*	*17*	*2*	*15,202*	*71*	*29*	*36*	*5*	*27,476*

Field Crashes versus Simulated Conflicts

Intersection crashes and conflicts were singled out of the entire data set to correlate field crashes with simulated conflicts. For most of the intersections, field crashes within 0.1 mile of the intersection were used. Exceptions were the intersections of SR-224 at Kimball Junction, Landmark Dr., and Olympic Park which were combined because the spacing between the intersections is less than 0.2 miles, which made it difficult to determine to which intersection to associate a crash.

The same approach was used for simulation data. Filtering zones were defined in the SSAM map window for each intersection with approximately the same limits (0.1 mile before and after the intersection). The filter in SSAM was applied and the data were extracted for further analysis. This was repeated for 5 representative days (mimicking traffic variability in the field) each of which had 10 random seed repetitions. Data for SCATS and Conventional TOD control were combined to get more points for a meaningful analysis. The objective of this task was not to draw differences between SCATS and Conventional TOD data but to show if there is a strong correlation between field crashes and simulated conflicts.

Figure 6 shows results from the analysis for all conflicts together and each of the conflict types separately. There are a few things that can be deduced from Figure 6:

- None of the correlations show a very strong trend between field crashes and simulated conflicts.
- Attempts to remove a few outliers (see Figure 6) have not improved the relationships - the opposite happened: coefficients of determinations are lower for cases without outliers.
- Correlation between rear-end crashes and conflicts is just slightly higher (0.52) than those from the two other conflict/crash types (0.49 & 0.47). The total conflicts and crashes exhibited the lowest correlation of all cases (0.199).
- Although these findings do not show a high correlation between field crashes and simulated conflicts, the results are not worse than what was observed in previous studies (Gettman et al. 2008). It seems that the underlying problems within microsimulation tools govern quality of estimated conflicts and remain a major source for future improvements.

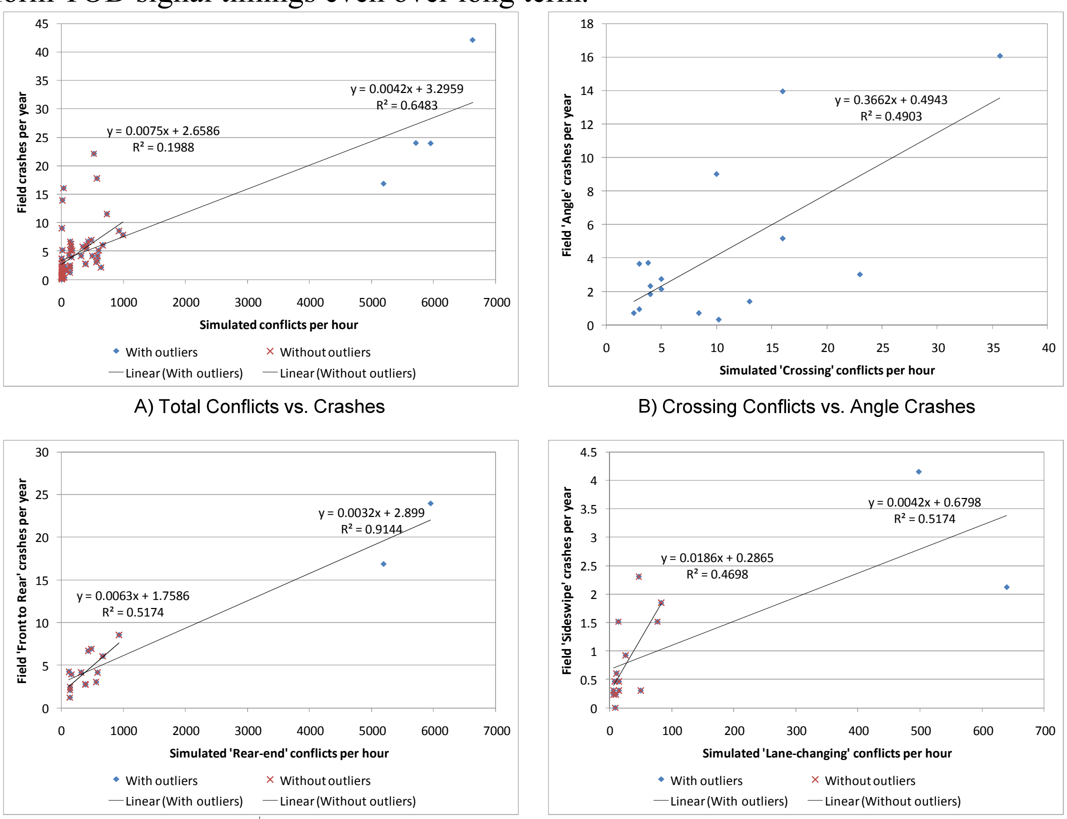
CONCLUSIONS AND FUTURE RESEARCH

When ATCS are evaluated, safety aspects of their performances are usually neglected due to difficulties in extracting meaningful conclusions from field crash data and/or limited availability to perform evaluation through simulation-driven surrogate safety measures. This study uses a software-in-the-loop approach to investigate quality of an ATCS deployed in the field (Park City). Signal timings representing SCATS and Conventional TOD control are modeled under varying traffic conditions based on field data. Simulation outputs are processed in SSAM for surrogate safety measures. Field data, from periods before and after SCATS was deployed, were retrieved and compared with simulated surrogate safety metrics. The following conclusions are reached based on the results of this study:

- SCATS outperforms Conventional TOD control in almost all performance metrics that measure efficiency of the traffic (e.g. stops, delay, travel time).
- SCATS generates fewer numbers of rear-end and total conflicts than Conventional TOD control, which can be attributed to longer cycle lengths deployed by SCATS.

- Conventional TOD control generates fewer crossing and lane-changing conflicts.
- Most of the differences between SCATS and Conventional TOD control are statistically significant and most of the findings can be reasonably attributed to operational characteristics of SCATS and Conventional TOD control.
- Field crash data shows an increase after SCATS was deployed in Park City. More analysis is needed to reveal reasons for this increase and find out whether the increase is significant. Authors speculate that multiple road construction activities during 2007 and 2008 may be a major reason for increase in crash frequency.
- Correlation indicators between field crashes and simulated conflicts are not very strong. However, for individual conflict types, they fall within the range (0.4 – 0.5) of correlations which were observed with traditional crash-prediction models and previous findings for SSAM surrogate safety measures.

More research is needed to investigate whether achieved benefits from SCATS can be sustained over long term. Considering that SCATS is a system that adapts to changes in traffic conditions (which have both efficiency and safety impact), it is speculated that SCATS would outperform TOD signal timings even over long term.



A) Total Conflicts vs. Crashes

B) Crossing Conflicts vs. Angle Crashes

C) Rear-end Conflicts vs. Front-to-rear Crashes

D) Lane-changing Conflicts vs. Sideswipe Crashes

Figure 6 Relationship between Field Crashes and Simulated Conflicts

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REFERENCES

American Association of State Highway and Transportation Officials (AASHTO). (2010). Highway Safety Manual, 1st Edition, Washington, D.C.

Anzek, M., Kavran, Z., Badanjak, D. (2005). "Adaptive Traffic Control as Function of Safety", Presented at ITS World Congress in San Francisco, USA. http://www.fpz.unizg.hr/manzek/ITS2005_SANFRAN_ANZEK_ADUPSIG_05.02-mmf_AMo5.02.pdf Accessed in April, 2011.

Bamfo, J.K. and Hauer, E. (1997). "Which is Safer in Terms of Right-Angle Vehicle Accidents? Fixed-Time or Vehicle-Actuated Signal Control", Proceedings of Canadian Multidisciplinary Road Safety Conference X, Toronto, Canada, 352-360.

Barceló, J., Casas, J., Ferrer, J.L., and Perarnau, J. (2003). "A Simulation Study to Evaluate the Performance of Adaptive Control Strategies for Traffic Safety Conditions in the Vielha Tunnel", Presented at Transportation Research Board Annual Meeting, National Research Council. Washington, D.C.

Bastable, A.J. (1980). "The Economic and Social impact of Dynamic Signal Coordination in Sydney." Proceedings of the 12th AARB Conference 10(4), 245-251.

Bonneson, J.A., and K. Zimmerman. (2004). "*Development of Guidelines for Identifying and Treating Locations with a Red-Light-Running Problem*", Report No. FHWA/TX-05/0-4196-2. Texas Department of Transportation, Austin, Texas.

Brehmer, C.L., Kacir, K.C., Noyce, D.A., and Manser, M.P. (2003). *Evaluation of Traffic Signal Displays for Protected/Permissive Left-Turn Control*, National Cooperative Highway Research Program (NCHRP) Report 493, Transportation Research Board, Washington, D.C.

Cooper, D., and Ferguson, N. (1976). "A conflict simulation model", *Traffic Engineering and Control*, Vol 17, 306-309.

Drummond, K., Hoel, L.A., and Miller, J.S. (2002). *A Simulation-based Approach to Evaluate Impacts of Increased Traffic Signal Density*, Research report of Virginia Transportation Research Council, Charlottesville, Virginia.

Fazio, J. and Rouphail, N. (1990). "Conflict simulation in INTRAS: Application to weaving area capacity analysis", *Transportation Research Record*, Vol. 1287.

Federal Highway Administration (FHWA). (2008). *Desktop Reference for Crash Reduction Factors*, Report No. FHWA-SA-08-0111 by U.S. Department of Transportation.

Finlay, A.B. (1984). "Evaluation of Increased Intergreen Time at Signal Sites Operating Close to Capacity", Report to Department of Main Roads, Sydney, Australia.

Gettman, D. and Head, L. (2003). "*Surrogate Safety Measures From Traffic Simulation Models"*, Report No. FHWA-RD-03-050, Federal Highway Administration, Washington, DC.

Gettman, D., Pu, L., Sayed, T., and Shelby, S. (2008). "*Surrogate Safety Assessment Model and Validation",* Final Report No. FHWA-HRT-08-051, Federal Highway Administration, Washington, DC.

Green, M. (2000). ""How Long Does It Take To Stop?" Methodological Analysis of Driver Perception-Brake Times", *Transportation Human Factors*, 2, 195-216.

Howard/Stein-Hudson Associates, Inc., (2010). *The Benefits of Retiming/Re-phasing Traffic Signals in the Back Bay*, Study prepared for Boston Transportation Department, Boston, MA. http://www.cityofboston.gov/Images_Documents/The%20Benefits%20of%20Traffic%20Signal%20Retiming%20Report_tcm3-18554.pdf. Accessed in April, 2011.

Jenkins, R.S. (1969). "*A Study of Selection of Yellow Clearance Intervals for Traffic Signals*", Report TSD-TR-104-69, Michigan State Department of Highways, Lansing, MI.

Kergaye, C., Stevanovic, A.Z., and Martin, P.T. (2009). "Comparison of Before/After versus On/Off Adaptive Traffic Control Evaluations: Park City Case Study", *Transportation Research Record: Journal of the Transportation Research Board*, 2128, 192-201.

Kergaye, C., Stevanovic, A.Z., and Martin, P.T. (2010). "Comparative Evaluation of Adaptive Traffic Control System Assessments through Field and Microsimulation. In *Journal of Intelligent Transportation Systems*, 14(2), 109-114.

Kosonen, I. and Ree, S. (2000). "*The potential for microscopic simulation in traffic safety and conflict studies*", Proceedings of Conference on Road safety on three continents, Pretoria.

Klunder, G., Abdoelbasier, A., Immers, B. (2006). "Development of a micro-simulation model to predict road traffic safety on intersections with surrogate safety measures", Paper (No. 1894) presented at ITS World Congress in London, UK.

Lowrie, P. R. (1982, March). "The Sydney Coordinated Adaptive Traffic System—Principles, methodology, algorithms", Paper presented at International Conference on Road Traffic Signaling, Institution of Electrical Engineers, London, England.

Lowrie, P. R. (1992). "SCATS - A traffic responsive method of controlling urban traffic", North South Wales, Australia: Roads and Traffic Authority.

Luk, J. Y. K., Sims, A. G., and Lowrie, P. R. (1982). "SCATS- Application and field comparison with a TRANSYT optimized fixed time system", Paper presented at International Conference on Road Traffic Signaling, Institution of Electrical Engineers, London, England.

Martin, P.T., and Stevanovic A.Z. (2007). "*SCATS Evaluation in Park City, UT*", (Adaptive Traffic Control V), Report (UTL-1107-92) prepared for Utah Department of Transportation, Salt lake City, UT.

Midenet, S., Saunier, N., and Boillot, F. (2011). "Exposure to lateral collision in signalized intersections with protected left turn under different traffic control strategies", *Accident Analysis & Prevention*, doi:10.1016/j.aap.2011.05.015.

Migletz, D. J., Glauz, W. D., and Bauer, K.M. (1985). *Relationships Between Traffic Conflicts and Accidents*, Report No. FHWA-RD-84-042, Federal Highway Administration, Washington, DC.

Miska, E., De Leur, P., and Sayed, T. (2002). "Road Safety Performance Associated with Improved Traffic Signal Design and Increased Signal Conspicuity", Presented at Institute of Transportation Engineers (ITE) Annual Meeting, Philadelphia, PA.

Moore, S.E., and Lowrie, P.R. (1976). "Further on the effect of coordinated traffic signal systems on traffic accidents." Proceedings of the 8^{th} AARB Conference 8(5), Session 26, 10-15.

Ozbay, K., Yang, H., Bartin, B., and Mudigonda, S. (2008). "Derivation and Validation of New Simulation-Based Surrogate Safety Measure", *Transportation Research Record: Journal of the Transportation Research Board*, 2083, 105-113.

Planung Transport Verkehr AG. (2010). VISSIM 5.30 User Manual. Karlsruhe, Germany: PTV.

Sabra, Z.A., Gettman, D., Henry R.D., and Nallamothu, V. (2010). *Balancing Safety and Capacity in an Adaptive Signal Control System* - Phase 1, Report No. HRT-10-038, Federal Highway Administration, Washington, DC.

Son, H., Kweon, Y-J., and Park, B. (2008). *Development of Crash Prediction Models using Real Time Safety Surrogate Measures*, Research Report No. UVACTS-15-0-70, Center for Transportation Studies, University of Virginia, Charlottesville, VA.

Stein, H.S. (1986). "Traffic Signal Change Intervals: Policies, Practices, and Safety", *Transportation Quarterly*, Vol. 40, No. 3, 433-445.

Stevanovic, A. (2010). "*Adaptive Traffic Control Systems: Domestic and Foreign State of Practice*", NCHRP Project 20-5: Synthesis Topic 40-03 – Transportation Research Board of the National Academy of Sciences, Washington, D.C.

Stevanovic, A., and Kergaye, C. (2010). “Evaluating Suitability of Microsimulation as a Tool to Replicate Variations in Field Traffic Flows.” Presented at Traffic Flow Theory and Characteristics Committee (AHB45) Summer Meeting, Annecy, France.

Stimpson, W.A., Zador, P.L., and Tarnoff, P.J. (1980). “The Influence of The Time Duration of Yellow Traffic Signals on Driver Response”, *ITE Journal,* 50, 22-29.

Tarko, A., G. Davis, N. Saunier, T. Sayed, and S. Washington. (2009). *Surrogate Measures of Safety*. White paper from Subcommittee on Surrogate Measures of Safety, Transportation Research Board of the National Academies, Washington, D.C.

Torday, A., Baumann, D., and Dumont, A-G. (2003). “Indicator for Microsimulation-based Safety Evaluation”, Presented at Swiss Transport Research Conference, Monte Verita /Ascona, Switzerland.

Wilson, C., Millar, G., and Tudge, R. (2006). “Microsimulation evaluation of the benefits of SCATS coordinated traffic control signals”, Paper 06-1984 presented at Transportation Research Board Annual Meeting, Washington, DC, USA.

Wortman, R.H., and Matthias, J.S. (1983). “Evaluation of Driver Behavior at Signalized Intersections”, *Transportation Research Record* 904, 10-20.

Zegeer, C.V., and Deen, R. (1978). “Traffic Conflicts as a Diagnostic Tool in Highway Safety”, Transportation Research Record No. 667.

Zhou, M. and Sisiopiku, V. (1997). “Relationship Between Volume-to-Capacity Ratios and Accident Rates,” *Transportation Research Record 1581*, Transportation Research Board, Washington, DC.

Zimmerman, K.H. and Bonneson, J.A. (2005). *In-Service Evaluation of a Detection-Control System for High-Speed Signalized Intersections*, Implementation Report No. 5-4022-01-1, Texas Transportation Institute, College Station, TX.