Measures of Effectiveness and Validation Guidance for Adaptive Signal Control Technologies

July 2013

U.S. Department of Transportation
Federal Highway Administration

FHWA-HOP-13-031

Produced by DTFH61-06-D-00004, Every Day Counts – ACS Lite Deployment Case Study and Field Evaluation
Federal Highway Administration
U.S. Department of Transportation

Cover art work by Donna Tan, SAIC.

Technical Report Documentation Page

1. Report No. FHWA-HOP-13-031	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle Measures of Effectiveness and Validation Guidance for Adaptive Signal Control Technologies	**5. Report Date** July 2013 **6. Performing Organization Code**
7. Author(s) Douglas Gettman, Edward Fok, Eddie Curtis, Kent Kacir Dan Ormand, Matthew Mayer, Erin Flanigan	**8. Performing Organization Report No.**
9. Performing Organization Name And Address Kimley Horn and Associates, Inc. 7740 North 16th Street, 3rd Floor Phoenix, AZ 85020 Under contract to Cambridge Systematics, Inc.	**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** DTFH61-06-D-00004
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Highway Administration Office of Operations 1200 New Jersey Avenue, SE Washington, DC 20590	**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code** HOP

15. Supplementary Notes

The COTM for FHWA is Edward Fok.

16. Abstract

As part of the Every Day Counts initiative, FHWA is promoting the implementation of Adaptive Signal Control Technology (ASCT) to improve traffic signal system operations in the United States. Among the other "low-hanging fruit" technologies in the Every Day Counts program (e.g., rumble strips, safety edge), ASCT technology has been in existence for many years but has not seen widespread acceptance. ASCTs have not historically been implemented widely due their cost and complexity (perceived or real) compounded by a lack of clear documentation of benefits. One reason for the uncertainty about benefits of ASCT is due to the wide variation in cost, complexity, and performance reporting methodologies of evaluation studies for ASCT.

In this project, generic measures of effectiveness and validation tools were developed for agencies to to validate that selected ASCT meet their performance objectives. In addition, the process and tools can be applied to traditional coordinated-actuated signal timing as well. The report identifies how each of the measures and processes can be used for validation of ASCT. Guidance on improving the state of the practice is provided.

This approach was tested at a field site in Mesa, Arizona where an ASCT system has been deployed for over one year. The City of Mesa allowed the test phase to include approximately 30 days during which the ASCT was turned off and background coordination patterns were used instead. Detailed findings for the validation approach are provided in Appendices to the main report.

17. Key Words Adaptive traffic signal control, traffic signal performance measures, evaluation of adaptive traffic signals, systems engineering, validation	**18. Distribution Statement** No restrictions.

19. Security Classif. (of this report) Unclassified.	**20. Security Classif. (of this page)** Unclassified.	**21. No. of Pages** 170	**22. Price** N/A

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

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CHAPTER 1. INTRODUCTION

PURPOSE

The intent of this project is to identify, develop, demonstrate and document measures of effectiveness that can be applied to validate the achievement of traffic signal operations objectives. Adaptive Signal Control Technology (ASCT) is an operational strategy that applies tactics aimed at achieving singular or multiple operations objectives. Validation, in the context of this project, is a component of the systems engineering process that evaluates if the system implemented addresses the operations objectives that were articulated as needs during the development of the concept of operations for the system.

Figure 1. Diagram. Systems Engineering Process with Needs and Validation Processes Highlighted.
(Source: Federal Highway Administration.)

This report documents the tools and methodology developed for validation and summarizes the testing of this approach and measures on a field site in Mesa, Arizona where an ASCT system has been deployed for over one year. The intent of the field study was not to evaluate the Mesa ASCT system specifically but rather to demonstrate the application of the validation measures and methodology to a real world implementation of ASCT. The City of Mesa allowed the test phase to include approximately 30 days during which the ASCT was turned off and background coordination patterns were used instead. These 30 days were randomly distributed over the course of two months. Tube counters and Bluetooth detectors were deployed temporarily for volume and travel time data collection. GPS probe data and phase timing and detector status data were collected during the test period. Green occupancy ratio, percent arrivals on green, platoon ratio, and route travel times and reliability metrics were calculated for five intersections in the test area.

BACKGROUND

The term Adaptive Signal Control Technology (ASCT), describes any system that collects data, evaluates traffic signal performance on the basis of one or more of the system's functional objectives and then updates signal timing in response to that evaluation. Adaptive systems were initially developed in the United Kingdom and Australia in the late 1970s and introduced to the United States in the mid1980s. Early deployments of Adaptive control systems in the United States were conducted as research or demonstration tests to evaluate their effectiveness and showed promising results. Compared to traditional systems, these ASCT were considered complex and difficult to maintain and operate due to communications and detection requirements. The FHWA sponsored the development of four adaptive control algorithms with the objective of reducing implementation cost and creating systems that were more consistent with US style traffic signal infrastructure.

ASCTs have not historically been widely implemented due their cost and complexity (perceived or real) compounded by a lack of clear documentation of benefits. In particular, the wide variation in cost, complexity, and performance reporting methodologies of evaluation studies for ASCT contribute to misunderstanding of the value and capabilities of available systems. Systems that were compared against poor existing timings get high marks and systems that were compared against excellent existing timings are perceived as having little value. Similarly, heavy oversaturated traffic conditions make challenging work for any signal timing approach, and failures of ASCT in such situations, in particular when they have been oversold to eliminate such congestion, tend to be notable.

As part of the Every Day Counts initiative, FHWA actively promoted the implementation of Adaptive Signal Control Technology (ASCT) to improve traffic signal system operations. A model system engineering process was tailored to facilitate the implementation of ASCT with the intent of addressing the risks that, when unchecked, have resulted in the failure or discontinued use of many ASCT deployments in the US. The model systems engineering documents discuss the development of agency objectives, a concept of operations, and system requirements to guide the design and implementation of ASCT. The second major component of the systems engineering process is then to verify that the selected system has met its stated requirements after system implementation and validate the system against the system's performance objectives and goals.

Verification is largely an inspection process by which the agency observes that the procured system includes the features that were requested in the requirements. Validation is the process by which the features and capabilities of the system are measured against the stated operational objectives of the agency in procuring and deploying the technology. The intent of this project is to develop a generic validation process and tools for agencies to use to validate that selected ASCT meet their performance objectives.

Table 1 summarizes the connection between agency objectives, measures of effectiveness, and field data used to calculate those measures.

Table 1. Mapping of MOEs to Objectives and Data Sources

MOEs	**Data Sources**	**Operational Objectives (FHWA-HOP-11-27, PG 94, References 3.4.4)**
• Route travel time • Route travel delay • Route average speed • Route travel time reliability	• Import travel time data from Bluetooth scanner • Import trajectory data from GPS probe	• Smooth Flow • Multiple objectives by TOD
• Link travel time, delay • Number of stops per mile on route	• Import trajectory data from GPS probe	• Smooth flow • Manage queues • Multiple objectives by TOD
• Traffic volume on route • Time to process equivalent volume	• Import count data from tube counter file	• Throughput • Manage queues • Multiple objectives by TOD
• Percent arrivals on green, by link • V/C ratio by movement • Platoon ratio, by link • Phase green to occupancy ratio by movement • Reliability of phase metrics	• Import high-resolution signal timing and detector data	• Smooth flow • Access equity • Multiple objectives by TOD

This document is organized as follows:

- Introduction (Chapter 1).
- The role of validation in implementation of ASCT (Chapter 1).
- Operational Objectives of ASCT and signal operations (Chapter 2).
- Description of generic measures of effectiveness that can validate system objectives (Chapters 3 and 4).
- Validation Guidance (Chapter 5).
- Future Research and Development (Chapter 6).
- Literature review of validation and evaluation studies in ASCT (Chapters 7 and 8).
- Overview of MOE tools and processes (Appendix A and B).
- Field testing of the validation methodology (Appendix C).
- MOE evaluations and findings (Appendix D).
- Validation results (Appendix E).
- Supporting results and additional details from the field deployment (Appendix F).

CHAPTER 2. TRAFFIC SIGNAL OPERATIONS OBJECTIVES THAT CAN BE APPLIED BY ASCT

Validation is a critical phase of the systems engineering process that an agency uses to identify that the system implemented fulfills the objectives and needs it was envisioned to achieve. The FHWA Model Systems Engineering Documents for Adaptive Signal Control Technology (ASCT) Systems (FHWA-HOP-11-27) identifies several operational objectives and strategies that are applicable to coordinated traffic signal systems and adaptive control. This document will offer guidance on how to carry out the validation process by demonstrating measures of effectiveness that are traceable to objectives and then providing a methodology for data collection and analysis. The outcome of the validation process is confirmation of whether or not stated objectives were satisfied.

To be effective, the validation process demands clear articulation of operational objectives. To the greatest extent possible, objectives should be stated in a manner that is Specific, Measurable, Achievable, Realistic and Time-bound (SMART). One method for formulating good objectives is to begin with a statement of goals for traffic signal operations. Goals for traffic signal operations state at a high level what the agency is trying to achieve as an outcome of the commitment of its resources. A logical framework is then used to derive objectives from goals, and then strategies and tactics from objectives. The framework thus provides traceability from goals to tactics. The scope of this report limits the validation to evaluating the achievement of objectives; however it logically follows that validation of objectives also suggests achievement of goals by implementation of specific strategies and tactics.

- Goals – What is trying to be achieved.
- Objective – What needs to be done to achieve the goal.
- Strategy – Capabilities put in place to meet the objective.
- Tactic – Specific methods to achieve the strategy.

GOALS FOR TRAFFIC SIGNAL OPERATIONS

The primary purpose of signalized intersections is to safely assign right of way to avoid conflicts. Conflicts are avoided by assigning segments of time when compatible movements of vehicles and pedestrians can safely travel through the intersection. As traffic signal control technology at both the intersection and system level has evolved, goals in addition to safely moving vehicles and pedestrian have become achievable through implementation of more carefully planned strategies and tactics. Goals that are oriented around improving efficiency by keeping traffic moving and minimizing stops and delay can be reasonably pursued and achieved without compromising safety. Well-articulated goals are ensured to be appropriate by considering the context within which they will be pursued. Context for goals of traffic signal operations could include technical capability, surrounding land use, user expectations and traffic demand conditions. Examples of traffic signal operations goals include:

1. Minimize Congestion.
2. Prevent or Delay Oversaturation.

3. Accommodate Long Term Variability.
4. Manage Incidents and Special Events.

Minimize Congestion

Congestion in the context of signalized arterial networks is the outcome of demand exceeding capacity at one or more intersections approaches resulting in the formation of destructive queues that propagate, increasing delay and causing impacts to safety and efficiency. The capacity of an intersection is directly related to signal timing and congestion can in fact be induced even in light to moderate demand conditions if signal timing is not appropriate for the demand condition.

Prevent or Delay Oversaturation

In many traffic situations, it is very difficult to prevent a system from becoming oversaturated. When demand vastly exceeds route and phase green time allocations, situations can quickly become unmanageable. ASCT can prevent or delay this situation by adjusting green time allocations for the saturated phases as the demand is increasing.

Accommodate Long-Term Variability

Traditional signal timing plans require maintenance as traffic patterns and land uses evolve. Communities in significant growth cycles have traffic patterns that change slowly over time as new businesses and residential areas are added to the community. Typical signal timing and review cycles (e.g., approximately three years) cannot keep up with the changes that occur in traffic patterns when those patterns are evolving on a monthly basis. ASCT should be able to provide less deterioration in efficiency over time as compared to re-optimization of fixed timings.

Manage Incidents and Events

All traffic systems at times experience incidents due to traffic crashes and a variety of other external influences. Planned special events such as concerts, sporting events, and community activities also cause significant challenges for signal timing plans with fixed parameters. ASCT is particularly suited to accommodate these abnormal situations.

TRAFFIC SIGNAL OPERATIONS OBJECTIVES

The Model System Engineering Document describes the following five traffic signal operations objectives that can be achieved by Adaptive Signal Control Technology. This list is not comprehensive, and is based on several high level goals including those listed in the previous section. One or more of these objectives may be related to the achievement of a goal. Chapter 3.5 of the Model Systems Engineering Documents describes a set of operational strategies that can be applied by an ASCT. The logical follow on to validation of an objective is that supporting strategies and tactics were successful; however, more rigorous evaluation and measures of effectiveness might be required that are beyond the scope of this report.

1. Smooth Flow (FHWA-HOP-11-27, page 25).
2. Maximize Throughput (FHWA-HOP-11-27, page 25).
3. Access Equity (FHWA-HOP-11-27, page 25).
4. Manage Queues (FHWA-HOP-11-27, page 25).
5. Variable Objectives (FHWA-HOP-11-27, page 26).
6. Changing Objectives under various circumstances – similar to number 5.
7. Maximize Intersection efficiency at isolated critical locations – Not addressed in this document.

Smooth Flow

This objective seeks to provide a green band along an arterial road, in one or both directions, with the relationship between the intersections arranged so that once a platoon starts moving it rarely slows or stops. This may involve holding a platoon at one intersection until it can be released and not experience downstream stops. It may also involve operating non-coordinated phases at a high degree of saturation (by using the shortest possible green), within a constraint of preventing or minimizing phase failures and overflow of turn bays with limited length, and with spare time in each cycle generally reverting to the coordinated phases.

Maximize Throughput

Maximizing throughput is achieved when the highest possible traffic flow is achieved across a cordon line. This is typically achieved by creating smooth flow along a route, but it may also be achieved by maximizing both through and turning movements along a given direction of travel. Satisfactory performance on a throughput maximization objective requires emphasis on maintaining large split times for phases that serve the intended direction of travel and maintaining offset and green-time relationships between adjacent intersections so that downstream queues do not affect the flow of vehicles along the critical route. Non-critical phases may have increased delays in order to provide the best possible level of service for the heaviest travel route.

Access Equity

Traffic signals are often provided so that major traffic generators along a street can have safe and efficient access to and from the arterial. In these cases, the objective is to equitably serve all traffic movements at each intersection. At the same time, coordination is generally provided along the arterial, but not at the expense of accessibility to local land uses. An example is a suburban retail shopping district that generates significant demand for left-turn and side-street movements. Intersections that serve significant traffic volumes on many movements, but are sufficiently isolated from other signals may also benefit from the the objective to optimize for access equity. Providing satisfactory performance on such an objective requires appropriate allocation of split time and less emphasis on maintaining opportunities for coordination.

Manage Queues

Where there are closely spaced intersections and particularly when a short link is fed by movements from various phases, it can be important is to ensure that queues do not block upstream intersections or movements or that upstream signals do not release traffic downstream when there is nowhere for those vehicles to go. Similarly, a queue management objective can include management of these situations, such as when a left turn bay spills over into adjacent lanes or when through movement queues prevent vehicles from entering a left-turn bay. Providing satisfactory performance on such an objective often requires tight constraints on cycle and phase durations to ensure that a large platoon does not enter a short block if it must be stored within that block and wait for a subsequent green phase. It may also involve “gating” actions, so that vehicles are stored upstream of the critical links because the upstream location has adequate queuing capacity.

Variable Objectives

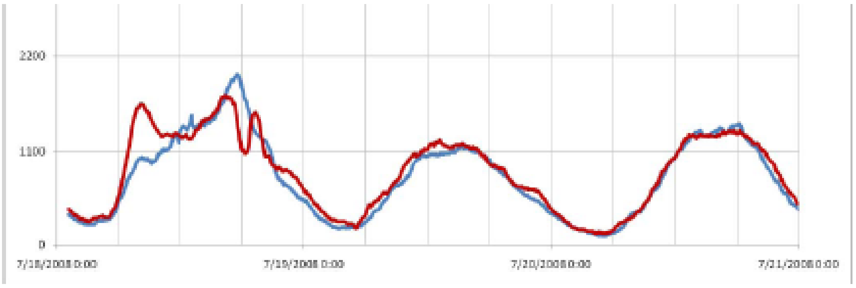
It is often the case that different objectives are appropriate at different times of the day and under different traffic conditions. An arterial road that provides access between a freeway and large residential areas, but also has traffic generators such as retail centers and schools, may require an objective of providing smooth flow or maximum throughput during the morning and evening peak periods, but provide access equity during business hours and on weekends.

CHANGING OBJECTIVES BY TIME OF DAY

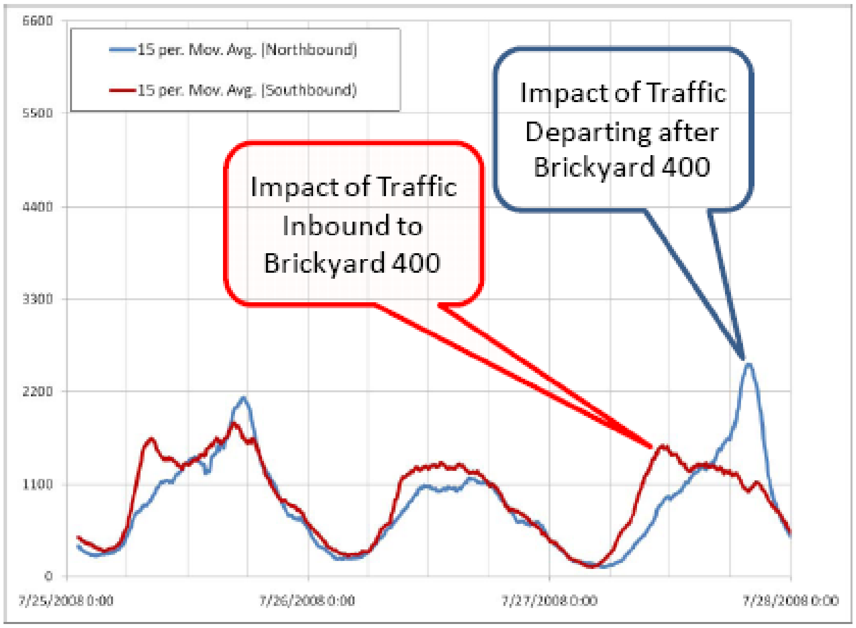
It is often the case that different objectives are appropriate at different times of the day and under different traffic conditions. An arterial road that provides access between a freeway and large residential areas, but also has traffic generators such as retail centers and schools, may require an objective of providing smooth flow during the morning and evening peak periods, but provide access equity during business hours and on weekends. Under these conditions, the ASCT may be required to accommodate switching objectives at different times of day. Most ASCT existing today do not explicitly include features or configurability to address this objective, although many systems will modify their actions to inherently achieve this objective based on detection of the field conditions.

LONG TERM VARIABILITY AND EVENTS

All traffic systems at times experience incidents due to traffic crashes and a variety of other external influences. Planned special events such as concerts, sporting events, and community activities also cause significant challenges for signal timing plans with fixed parameters, particularly when the egress from the event cannot be easily predicted (e.g., overtime). Many agencies address these situations with manual approaches (policemen, TMC operators), which can be expensive. ASCT are particularly suited to accommodate these abnormal situations. Figure 2 illustrates the typical shifts that occur in traffic demand due to special events (Bullock et al., 2008). The top graph indicates the directional flow along the routes to the Brickyard 500 on a normal day. The bottom graph indicates the directional flow along the routes to the Brickyard 500 on the day of the event.



a) July 18-20, 2008



b) July 25-27, 2008

Figure 2. Line Graph. Comparison of normal (top) and special event traffic (bottom). (Source: Wasson et al., 2008.)

SUMMARY OF OPERATIONAL OBJECTIVES FOR ASCT

While the implementation of ASCT will generally be expected to improve the performance of your traffic system, there are a wide range of operational objectives that can be addressed by deploying ASCT. In all cases, the key characteristic of the traffic situation that is addressable by ASCT is variability. Something in the traffic system changes or is changing, either quickly in minutes or slowly in days, months, or years, and the existing signal timings are not appropriate for the new situation. This results in unnecessary degradation to the traffic performance. Identifying appropriate objectives for the deployment of ASCT is important for achieving the results you anticipated. Collecting performance measurements that validate that the system meets those objectives is the second component of effective deployment of ASCT.

In the history of ASCT deployment, it has not always been the case that objectives for ASCT deployment have been explicitly stated. Further, MOEs that have been collected and reported don't always validate that the system met the objectives. In addition, multijurisdictional deployments often do not have consensus among the stakeholders as to what the operational objectives will be. In the next section, we summarize a review of representative (not comprehensive) literature in evaluation studies for ASCT. This review is intended to identify strengths and weaknesses of past studies with the goal of identifying a recommendation for best practices in evaluation of ASCT and signal timing. From these strengths and weaknesses of past approaches, tools were developed that can help facilitate matching operational objectives with MOEs.

CHAPTER 3. METHODS FOR VALIDATION OF ASCT DEPLOYMENTS

Over the years there have many attempts at measuring performance associated with different adaptive signal control technologies. Most of the literature has been produced by agencies, consultants, and academics. A summary of representative studies done by academics, consultants, and agency staff is presented in this section. A more detailed literature review is provided in Chapters 7 and 8.

Most studies spend a substantial amount of time describing the corridor characteristics and much less time describing existing signal timings and common areas of substandard performance. Furthermore, most studies do not articulate or analyze the specific modifications made by the ASCT that resulted in the improvements to the conditions as reported by the MOEs.

Most studies have focused on the key metrics associated with standard traffic operations – stops, delay, and travel times. Some studies have also tried to include safety effects including crashes. Collecting route travel time data is the most common evaluation approach for traffic studies. In most studies, multiple "probes" travel the corridor collecting start time, time at which each signalized intersection is encountered, and the time to reach the stopping point of the corridor. The collection of travel time data using probes requires a careful consideration of the number of travel runs necessary to be considered statistically significant, but many studies estimate the runs based on reasonableness and cost. These relatively low numbers of runs can be used to compare averages, but are not effective in assessing improvements to travel time reliability that may result from application of ASCT. Further, when budgets are limited travel time runs are most commonly collected only during peak periods which may not reflect the capability of the ASCT to improve conditions during the shoulder and off-peak times, where ASCT may actually have more impact when demands are more variable.

In addition, travel-time varies with traffic volume. Some studies have considered volumes in validating that two conditions are statistically similar, but volume is not typically used to augment the travel data to compare how before and after treatments vary with volume. Newer approaches such as (Fehon et al., 2010) use volume data explicitly. An estimate of total stops can be also be made using the probe data and the route volume.

Many studies report only arterial end-to-end travel times and neglect collection of data on routes that have different origins and destinations in the system and combinations of turning movements. Only a limited number of studies have considered multiple paths through an ASCT network (Hunter et al., 2006). When vehicle re-identification technologies are used instead of probe vehicles, stops cannot be computed, so reductions or changes in delay and travel time are only typically reported.

Most studies augment route travel times with collection of a limited amount of side-street performance data using traditional manual observation techniques – counting vehicle queues and estimating delays. Due to the manual labor involved, all studies are limited in the duration of the data collection due to project budget. Pedestrian delay is typically measured using a stopwatch technique.

These simple techniques are effective, but just cannot be used for long periods of time due to cost and the need of humans to take breaks. Videotaping can alleviate some of the need for on-site observers and allow some “fast-forward” time savings, but still cannot be used to evaluate a system for extended periods. High-resolution phase timing and detection data that is now becoming available from controllers, ASCT, and other signal systems can be used to reduce the manual effort to collect such measures. Video-analytic methods are emerging but have yet been proven reliable.

Studies that report queue lengths as performance measures are almost always counted manually with observers. NCHRP 3-79 recommends use of videotaping and manual post processing. A few vendor technologies are emerging that claim the capability to count turning movements and queue lengths automatically from video cameras images. Such systems have not been evaluated and validated extensively enough to consider such automated methods as part of this process at this time.

Almost all studies approach the data collection efforts in a “before” and “after” format and the data collected is quite limited in duration. In particular, studies neglect the collection of measures that reflect the ASCT capabilities to modify its operation to efficiently accommodate variations. It is also not uncommon to collect the “before” conditions and “after” conditions with several months of time in between the two studies. Over this time, travel demand can, and typically does, change due to a variety of reasons, such as site development and seasonal changes. It has also been estimated that signal timing performance degrades approximately 3 percent per year, so waiting longer to collect “after” data will typically show more substantial improvements.

To get around the issues related to before/after studies, several studies have begun to study performance using on/off techniques. While an on/off approach may be more scientifically defensible, such a study is more difficult to support politically by the agency owners. Laypeople and nontechnical stakeholders frequently view the intentional disabling of a technology as imprudent.

The largest contributor to the uncertainty about the benefits of ASCT is due to the quality of timings that the new system has been compared to. Some reports of hugely successful deployments (90 percent reductions in stops, etc.) have compared the ASCT to poorly configured or significantly outdated timings. Other studies report only modest improvements due to ASCT. These studies most commonly compare the ASCT to recently optimized timings or timings that are already largely suitable for typical conditions. Traffic engineering principles are based on sound theory, so there is no reason to assume that an ASCT can outperform traditional signal timing under stable-flow conditions. Both situations are accurate assessments of ASCT value, but tend to inappropriately distort comparisons between systems when they are used to decide which system to implement.

Reporting percent differences contributes possibly the most to the uncertainty of ASCT performance since percentages amplify differences in small numbers. While percentages are easy for human brains to process, there is definitely a need to identify reporting methods that allow fairer comparisons of performance. Some evaluations have used other ways of aggregating performance (MnDOT, 1995; NCHRP 03-90, in press) such as accumulating the number or percentage of links that were "better," "worse," or "same" into bins by time of day and direction of travel. Other studies have explored similar aggregation methods and data presentation methods for summary performance reporting (Papamichail et al., 2009; Pesti et al., 1999).

Most studies also make an attempt to extrapolate the performance improvements of a given "after" performance to a benefit/cost ratio and to compute aggregate impacts to emissions and fuel savings. These extrapolations typically assume that the percentage savings would accrue at the same rate for the system life cycle, which is probably not accurate since most agencies retime signals on some schedule (three to five years) or due to repeated trouble calls

Finally, it was found that most agencies and evaluators did not articulate specific objectives or provided targets for performance on certain measures.

SUMMARY OF LITERATURE REVIEW

From the literature, the following common themes for best practices and pitfalls to avoid were identified (see Table 2). The recommended validation approach will use the best practices and address the common challenges.

Table 2. Issues Identified in Literature Review

Issue	Accommodation
Limited articulation of operational objectives	Validation of ASCT effectiveness in meeting specific operational goals
Side-street performance usually measured manually	Use high-resolution signal phase and detector data to estimate performance directly and 24/7.
Limited number of probe data runs	Combine probe runs with vehicle re-identification equipment to fill in gaps 24/7; smartphone apps for data collection with only one person.
Limited/no focus or study of abnormal conditions and incidents	Stage/simulate abnormal conditions if mitigation is an objective.
Limited/no focus or study of pre- and post-peak-period performance	Recommend measurement of new metrics for pre- and post-peak congestion management performance
Presentation of percentage improvements skews comparisons when "before" timings are poor	Use measures that can be compared "apples to apples."

Table 2. Issues Identified in Literature Review

Issue	**Accommodation**
Separation of data in before and after time periods	Use ON/OFF or ensure that after data is collected as close as possible to before data collection.
Limited use of volume data for aggregate performance assessment	Provide methodology for estimation of variation in performance and “total” system performance using volume data collection.
Queue performance usually measured manually	Provide automated methods for queue estimation from high-resolution signal phase and detector data.
Extrapolation methods for B/C estimation make unrealistic assumptions	Provide recommended methodology for more accurate B/C estimation
No emphasis on reliability of performance	Provide recommended methods to estimate reliability

CHAPTER 4. CANDIDATE MEASURES OF EFFECTIVENESS FOR VALIDATION OF OPERATIONAL OBJECTIVES

A variety of MOEs have been used to measure ASCT performance. New measures and approaches are emerging as high-speed IP technology has enabled easier access to high-resolution signal timing data. The following MOEs are presented and identified as candidate measures to validate that ASCT meet their operational objectives. Note that the use of the word "validate" is important here. In order to validate that an ASCT or any mitigating strategy has met its operational objective it does not necessarily need to have a base scenario to be compared with. If the validation is done with respect to a baseline performance, then that traffic condition needs to be as statistically similar to the scenario that is controlled with the ASCT as possible. As discussed in the previous section, this is one of the main challenges of evaluation studies. Simulation testing is most suited for this kind of validation comparison, but simulation testing is expensive, time-consuming, and results in yet a different set of issues due to modeling assumptions, behavioral rules and input data.

To the extent that data and corresponding MOEs are available for a statistically similar base scenario, as long as the ASCT provides acceptable performance on the objective, the ASCT should be considered to be validated. If data and corresponding MOEs are not available from a baseline scenario, which would be most common for incidents, similar situations may have to be created artificially in the field. For example, using traffic cones or agency vehicles to create simulated breakdowns or lane closures for both situations with and without ASCT might be used as a surrogate technique for validation of the functionality.

In addition, validation does not imply any absolute measurement that an ASCT is superior to any other available option, including implementation of alternative fixed timing plans or any of the other wide ranging features of actuated-coordinated controllers. In many cases, simple adjustments to actuated operation can go a long way towards accommodating variability without the expense and complexity of adding ASCT. Many of these valuable features are identified in FHWA-HOP-11-027.

Each ASCT has a different set of formulas, rules, and optimization functions that contribute to the effectiveness of the timings that are implemented in the field at any time. It cannot be known implicitly what the optimal response could have been without a) perfect knowledge of the state and intentions of every system user, and b) a specific optimization goal is agreed upon. The performance of one ASCT versus another cannot be compared absolutely unless they are all given exactly the same problem to address. This cannot be done in any real world situation since no two systems can be brought to bear on exactly the same traffic at exactly the same time.

Table 3 summarizes candidate MOEs for each operational objective. Each MOE is denoted as a candidate since it is not necessary to calculate or compare all of the measures to validate the functionality of a system. Each MOE also has a different level of difficulty in implementation or interpretation. In the sections following the table, we provide a definition of each measure and some discussion of the data requirements to compute the information. The measures and techniques identified as candidates are all generic measures that are not part of the calculation engine of any particular ASCT system. Measures from ASCT systems that are described in the open literature are not considered candidate MOEs in order to keep the process as generic and transparent as possible.

Table 3. Candidate MOEs for Validation of Operational Objectives.

Operational Objective	**Candidate MOEs**
Smooth Flow	Route travel time, delay, average speed Link travel time, delay, average speed Green bandwidth on route Percent arrivals on green, by link Platoon ratio, by link Number of stops per mile on route
Access equity	Phase green to occupancy ratio by movement V/C ratio by movement Queue length by movement
Manage queues	Queue length by movement Number of stops per mile on route Time to process equivalent volume
Throughput	Time to process equivalent volume Traffic volume
Changing objectives by TOD	Covered by MOEs from other objectives

ROUTE TRAVEL TIME

Route travel time is defined as the time it takes to travel from a given origin to a given destination along a given route. Travel time is the most commonly used measurement in evaluation of traffic system performance. The best possible travel time in a traffic system is defined as the time it would take to travel from origin to destination at the free-flow speed for each link in the route. Travel time is defined with respect to a given route distance; so it is not a measure that can be compared from one site to another. Similarly, route travel time can depend on the level of traffic demand.

There are several technologies that are available for measurement of travel time. They generally fall into one of two groups:

- GPS probe vehicles.
- Vehicle re-identification technology.

Probe vehicle data is good for collecting detailed performance for each component of a route but is expensive to collect to comprehensively cover the various traffic situations (a.m., p.m., mid-day, off-peak, weekend, traffic patterns, day of week, etc.) of interest. Probe vehicle data sources include laptop applications, phone and tablet apps, and proprietary ATIS data.

Vehicle re-identification technology (Bluetooth, vehicle signatures, license plate reading) is able to record 24/7 information for the end-to-end trip time on a route, but cannot provide detailed information on vehicle performance in between the end points of the trip. Based on the technology type, vehicle re-identification methods can only record a sample of the total traffic stream. In most situations, this sample should be considered adequate for the purpose of validating objectives. As early as 2009, there are literatures that describe data collection using Bluetooth-enabled MAC address readers, GPS-enabled data loggers and signal systems with better logging and vastly expanded storage capabilities. The Bluetooth devices are described in Tarnoff (2009) and Caltrans (2010). Other techniques using magnetometers and license-plate readers report positive re-identification, from one array to another can range from 50 to 70 percent depending on the spacing and geometry of an arterial.

ROUTE AVERAGE SPEED

Route average speed is simply the route distance divided by the travel time. Average speed can be measured by GPS probe data and vehicle re-identification systems. Similar to travel time, average speed is sensitive to traffic volume, speed limit, and link types.

LINK TRAVEL TIME/LINK AVERAGE SPEED

Link travel time and link average speed is defined as the travel time (average speed) from the beginning of a street link to the limit line or stop bar of the next traffic control device. Notionally a route contains more than one link. Technologies for collecting this data are the same as for route travel times and average speeds. System advance detection and mid-block speed trap sensors are also frequently used to measure link average speed (as well as volume and occupancy levels). Single-zone sensors are not particularly accurate in recording speed estimates as they rely on assumptions of average vehicle length. Various types of sensor technology (video, loops, radar, etc.) induce their own biases as well. Other sources should be consulted for more information on sensor technology benefits and challenges.

ROUTE TRAVEL DELAY

Route travel delay is defined as the difference between the time it takes to travel from a given origin to a given destination along a given route, and the time it would have taken to travel that route at the free-flow speed for each link in the route, without having to stop. Technologies for collecting this data are the same as for route travel times and average speeds.

LINK TRAVEL DELAY

Link travel delay is defined as the difference between the time it takes to travel from the beginning of a given link to the limit line or stop bar of the end of the link, compared to the time it would have taken to travel that link at the free-flow speed. Technologies for collecting this data are the same as for route travel times and average speeds.

ROUTE TRAFFIC VOLUME

Route traffic volume is defined as the number of vehicles that travel from the origin to the destination of a route in a given period of time. Throughput is measured as the rate of flow, so volume is the direct measurement of throughput.

There are several technologies that are available for measurement of traffic volume. They generally fall into one of two groups:

- Point sensors (road tubes, mid-block sensors, exit sensors).
- Vehicle re-identification technology.

Road tubes, mid-block sensors, and exit sensors (i.e., sensors that measure the traffic on the departure leg of an intersection) are frequently used to measure traffic volume. Most systems can be configured to provide reliable data. Various types of sensor technology (video, loops, radar, etc.) induce their own biases. Other sources should be consulted for more information on sensor technology benefits and challenges.

For the purpose of ASCT validation, the main challenge of using point sensors for measuring traffic volumes on a route is that this technology does not accurately reflect the origin-to-destination volume, and rather reports the total volume that crosses that point during a given time. This would thus include traffic from every other route with that destination including side-street turning flows. Methods such as identified by (Fehon et al., 2010) can be used to generate estimates of total travel time and total delay impacts from probe runs and volume collection.

Vehicle re-identification technology (Bluetooth, vehicle signatures, license plate reading) is better than point detection at identifying particular trips on a route, but cannot capture the exact number of vehicles on the route because they can only record a sample of the total traffic stream. In most situations, this sample should be considered adequate for the purpose of validating objectives, rather than generating total impacts that can be used for further extrapolation for B/C estimation.

TIME TO PROCESS EQUIVALENT VOLUME

A variation of the measurement of throughput for a fixed time period is to measure the time in which it takes for a given number of vehicles to be processed by a system. This MOE allows comparison of two methodologies to react to incident or event conditions, or to manage the shoulders of the peak period. This metric is simply a variant of throughput, so it can be computed from the same technologies and data used to compute throughput. It will be important to aggregate the volume data in small enough intervals for accurate comparisons. Five-minute summaries should be sufficient.

GREEN BANDWIDTH ON A ROUTE

The bandwidth (number of seconds) of the green time along a route can be used as a surrogate indicator for the performance of the travel on a route. Bandwidth only indicates opportunities for progression, rather than the real performance. Most past evaluation studies have not used green bandwidth in any performance assessments. Since ASCT are continually modifying the splits, offsets, and other parameters, the green bandwidth on any route will be changing. Green bandwidth can only be evaluated by obtaining high-resolution phase timing data (i.e., event-based data on each interval change or second-by-second status) from the ASCT or underlying signal system.

PERCENT ARRIVALS ON GREEN

A measure of individual phase progression performance is the percent arrivals on green. This measure estimates the proportion of vehicles that arrive to a green light versus the proportion that arrive to a red light. This provides an estimate of total stops, and identifies the quality of the offsets between two coordinated intersections. This measure can be obtained through monitoring of high-resolution occupancy measured by advance detectors on the coordinated approach and high-resolution phase timing data from the ASCT or underlying signal system. This concept is illustrated in Figure 3.

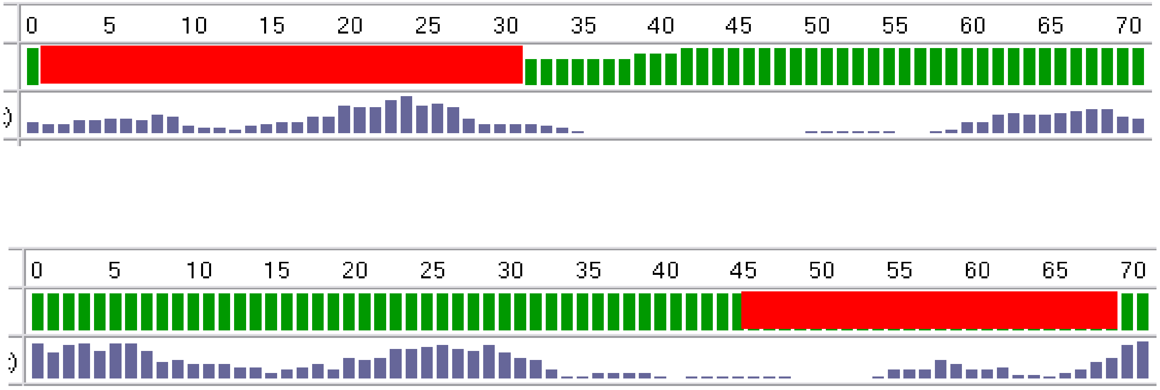


Figure 3. Illustration. Illustration of Data Used to Calculated Percent Arrivals on Green. (Source: Kimley-Horn and Associates, Inc.)

From several cycles of cycle-by-cycle occupancy data for each second in the cycle, the average occupancy for each second over a cycle is calculated. This is illustrated in Figure 3. Similarly the proportion of time when the coordinated phase is green over each second of the cycle is calculated for the same time interval. This is illustrated in Figure 3 in the row below the cycle time. The average percent arrivals on green is then calculated by the percentage of the total detector profile that is correlated with a green phase indication after shifting the detector profile several seconds to account for the travel time from the detector location to the stop bar. Alternatively, one could calculate the percent arrivals on green for each cycle, and then average the percentages to obtain an average percentage of arrivals on green for a time period.

Simple calculations for percent arrivals on green do not inherently take into account queues at the stop bar that might fill in from side-street phases during the red interval. As such, shifting the arrival profile forward based on the travel time to the stop bar will slightly overestimate the quality of nonstop progression on a given link. Other research, such as work by University of Minnesota (Liu and Ma, 2009), attempts to generate virtual vehicle profiles (similar to those drawn on time-space diagrams by your optimization software of choice) that estimate the percentage of arrivals on green and the length of the queue. This technique is discussed further in the section on queue measurements.

The percentage of arrivals on green provides an estimate of the coordinated performance of a specific link, but not on a whole route. Since the percentage of arrivals on green is a ratio measure, it is comparable across a range of cycle times and green times. Such a measure can be automatically and continuously computed from high-resolution data and thus does not require probe information or ancillary vehicle re-identification systems and equipment. The reader is pointed to the papers referenced in this report for more detail.

PLATOON RATIO

Platoon ratio is a measure of individual phase progression performance derived from the percentage arrivals on green such that Rp=%arrivals_on_green*(C/g) when C is the cycle time and g is the green time (Smaglik et al., 2007). This measure is derived from the HCM definition of arterial performance (ITE, 2000; 2010) as illustrated in Table 3. Smaglik, Bullock, and Sharma (2007) identified the use of arrival type (AT) as a better means to measure the effectiveness to describe the quality of progression from one signalized intersection to the next along a coordinated corridor. The AT parameter is based upon the percentage of vehicles arriving during the green indication, when they arrive during the green interval, and the density of the arriving platoon. The AT parameter is important to signal operators for two reasons.

Table 4. HCM Arrival Type to Platoon Ratio Assignments.

Arrival Type	Range of Platoon (R_p)	Default Value (R_p)	Progression Quality
1	≤0.50	0.333	Very poor
2	>0.50-0.85	0.667	Unfavorable
3	>0.85-1.15	1.000	Random arrivals
4	>1.15-1.50	1.333	Favorable
5	>1.50-2.00	1.667	Highly favorable
6	>2.00	2.000	Exceptional

Source: ITE Highway Capacity Manual 2000.

First, it provides a method for accounting for delay experienced along a coordinated arterial for analysis using the HCM delay equations. Second, it provides a measurement that can be used to assess the performance of an arterial signal system's progression quality. However, it has been shown that collecting accurate data on quality of progression using the methodology set forth in Chapter 15 of the HCM is difficult and extremely labor-intensive, as it requires the evaluation of the performance of multiple approaches over several time periods. The Smaglik et al. (2007) study concluded that an on-line quantitative progression quality assessment tool is needed, which is enabled by access to high-resolution phase timing and detector information. Similar to percent arrivals on green, the measure requires no probe data or vehicle re-identification equipment.

Similar to percent arrivals on green, the platoon ratio applies to an individual link, but not a whole route. Since the percent arrivals on green is a percentage or ratio measure, and the platoon ratio is a simple transformation of that, the platoon ratio is comparable across a range of cycle times and green times. Figure 4 illustrates how the arrival type can be used to graphically compare two signal timing conditions.

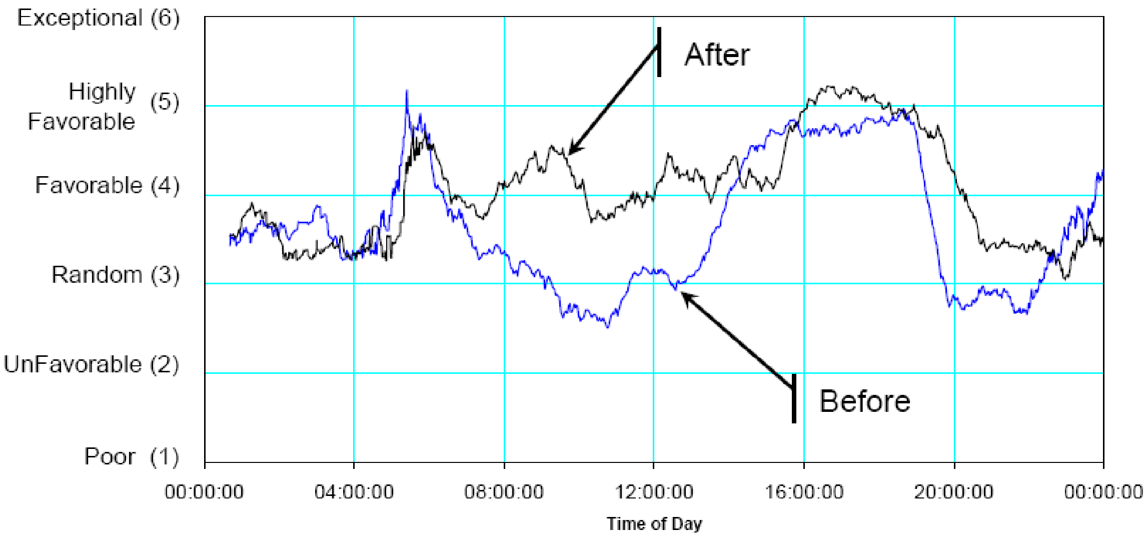


Figure 4. Illustration. Arrival Type Performance Before and After Offset Modifications (Source: Bullock et al., 2008.)

NUMBER OF STOPS PER MILE

The number of stops on a route is an important performance measure for smooth flow and queue management objectives. In most literature, a "stop" is defined as a prolonged period of time that the vehicle is traveling less than some threshold speed (e.g., <three mph, for >10s). Joining the back of a queue and then creeping a few feet every few seconds is not typically recorded as multiple stops unless the vehicle proceeds above the threshold speed for a prolonged period (e.g., 10s) before returning to a speed below the threshold again. Recording the number of stops requires high-resolution GPS probe data that can report vehicle location and speed on a frequent basis, at least every one to three seconds. The total number of stops on a route is an important measure, but it is not comparable from one location to another due to the dependency on the route distance. The number of stops per mile is suggested to provide a more comparable, generic measure.

PHASE GREEN OCCUPANCY RATIO

The degree of saturation is the primary indicator of phase performance from the historical HCM (2000; 2010). The degree of saturation indicates the suitability of the split time to the arriving demand but is difficult to measure directly since it requires knowledge of arrival demand (not served volume). One surrogate for this is the green occupancy ratio (Smaglik et al., 2011). This measure is simply the ratio of the detector occupancy during the green phase to the total green available in the split, with a minor adjustment for the "unusability" of green time that occurs between following vehicles. This metric is typically computed using sensors at the stop bar and requires high-resolution phase and detection data, particularly occupancy data.

As shown in Figure 5, the green occupancy ratio (GOR) overestimates, but reasonably tracks, the volume to capacity ratio. The GOR is also affected by the length of the detection zone. GOR is a measure that ranges by definition from zero to one. As defined, there is no available extension to this methodology for capturing degree of saturation values that exceed one.

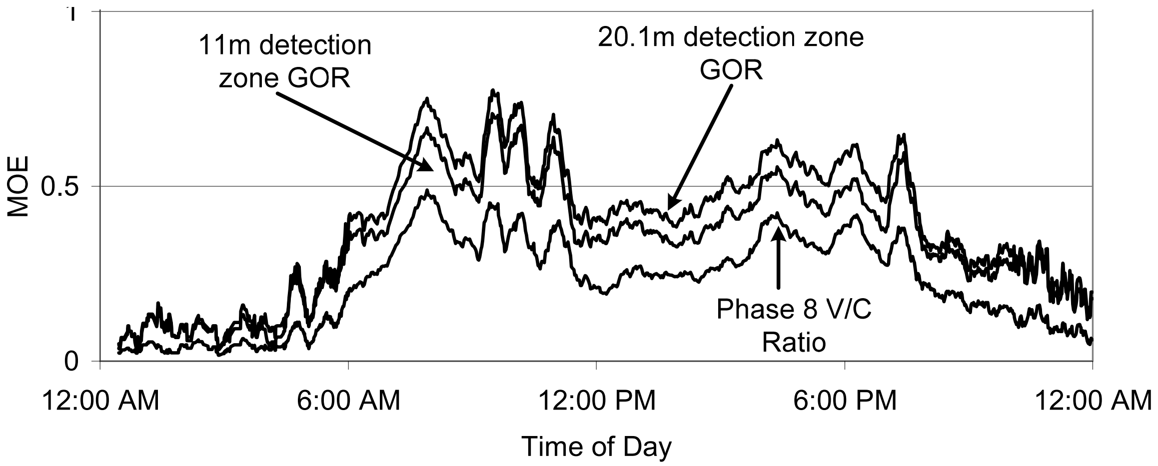


Figure 5. Illustration. Illustration of Comparison of Detection Length on Calculation of GOR and V/C
(Source: Smaglik, 2011.)

SERVED VOLUME TO CAPACITY RATIO

Served Volume to Capacity ratio is another surrogate for the degree of saturation. (Smaglik et al., 2011) also shows that this measure can be computed from high-resolution phase and detector data, such that:

$$\left(\frac{v}{c}\right)_l = \frac{q_g}{\left[s_l * \left(\frac{g_l}{C}\right)\right]} = \frac{(v_l * C)}{(s_l * g_l)}$$

Figure 6. Equation. Served Volume to Capacity.
(Source. Smaglik, 2011.)

Where v_l is the observed volume during green, g_l is the green time, C is the cycle time, and s_l is an estimate of the saturation flow rate. q_g is equivalent to v_l. Since this measurement is based upon volume or counts, long detectors at the stop bar or limit line are not particularly suited for measurement. Counting sensors or very short zones should be used for this purpose.

QUEUE LENGTH BY MOVEMENT

Queue length is an important MOE for a variety of objectives. Almost no previous evaluation approaches discuss measurement of queues except on side-streets using manual observer (HCM) methods. Many ASCT use estimates of queues to model traffic performance and optimize timings. Queue length is typically reported as a distance (feet, meters) or as a number of vehicles (or passenger vehicle equivalents, in the case where trucks and buses are in the queue). Accurate measurement of queues has historically been difficult to do due to a wide range of factors, including mid-block sources, sinks, turning traffic, and technology. Some video systems can be configured to measure and report queue distances but are constrained by their field of view.

NCHRP 03-79 describes the input-output and hybrid input-output calculation methods that can be used to compute queue lengths up to the point of the advance detector, using high-resolution phase timing and detector information (Bonneson et al., 2005). If the detector is placed as an exit detector, a queue the entire length of the link can be measured. Placement of detection at exit points is typically cost-prohibitive, unless already required by the ASCT itself.

Another queue estimation method is available that can determine queue length from advance sensors (Liu and Ma, 2009). This method uses a macro traffic model based on the fundamental diagram to estimate the length of the queue from high-resolution phase and detector data (see Figure 7).

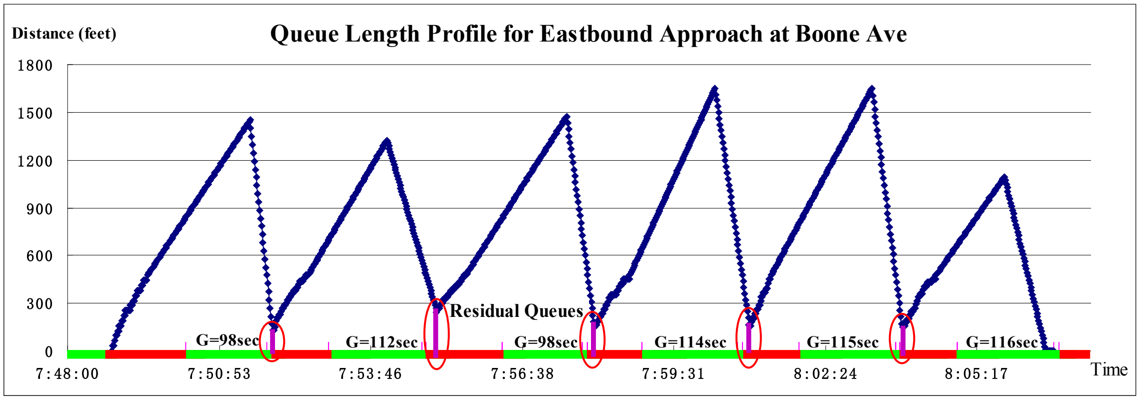


Figure 7. Illustration. Example Queue Length Estimation Results.
(Source: NCHRP 03-90 Final Report, pending.)

This method has been shown in field trials to produce acceptable results on high-speed arterials. The University of Minnesota is currently testing the performance in locations with short links and grids; some testing on short links was done as part of NCHRP 03-90 (publication pending). The concept has been patented and a small business has been established to commercialize the technology, although the algorithms are available in the open literature. Two of the strengths of this method are the ability to estimate queues further upstream from where the detector is placed, and the ability to estimate quantitative measures of oversaturation. One weakness of the approach is that currently the theory can only estimate a queue that is at maximum two times the length that can be serviced in one green phase.

OVERSATURATION METRICS

The degree of saturation (DoS) for a phase can be greater than one when the demand exceeds the capacity. This is commonly referred to as oversaturation. DoS of 1.3 for example would indicate that there is 30 percent more demand for the phase than the green time will allow. In this situation, the queue will grow without bound unless the green time is increased, or the arrival rate is decreased. Preventing the onset of oversaturation and recovering from oversaturation is one of the key objectives that may be able to be addressed by deployment of ASCT. Limited discussion of quantification of these situations is available in existing literature.

By modifying green times, ASCT can prevent overflow queues from occurring or flush out queues faster in recovery. There are very limited techniques for measurement of oversaturation. As part of NCHRP 03-90, two metrics for oversaturation intensity were developed. One metric represents the amount of green time in the cycle that is spent servicing the queue from the previous cycle (Temporal Oversaturation Severity Index) and the other metric represents the amount of green time in the cycle that is wasted because of downstream blockage (Spatial Oversaturation Severity Index) [publication is pending]. The technique was developed as an extension to the queue estimation work of Liu and Ma. Table 5 illustrates typical results for these metrics for a short link between two intersections that experiences both an overflow queue and downstream blockage due to a short 15-minute surge in traffic demand.

Table 5. Example Quantitative Measures of Oversaturation.

Cycle Start	Available Green(sec)	OSI: Created by Overflow Queue			OSI: Created by Spillover	
		Overflow Queue	Unusable Green (sec)	T-OSI (%)	Unusable Green (sec)	S-OSI (%)
17:06:31	136	0.0	0.0	0.0	0.0	0.0
17:09:31	136	0.0	0.0	0.0	3.0	2.2
17:12:31	136	89.6	0.0	0.0	28.0	20.6
17:15:31	136	164.3	7.2	5.3	28.8	21.2
17:18:31	136	0.0	13.1	9.7	15.0	11.1
17:21:31	136	180.4	0.0	0.0	41.7	30.6
17:24:31	135	165.3	14.4	10.7	34.1	25.2
17:27:31	139	138.2	13.2	9.5	25.2	18.1
17:30:31	120	125.3	11.1	9.2	16.3	13.6
17:33:31	141	0.0	10.0	7.1	8.6	6.1
17:36:31	135	0.0	0.0	0.0	0.0	0.0

Source: Liu, Wu, and Gettman, 2010.

One limitation of the indices is that these metrics only scale from 0 to 100 percent. Extended modeling concepts would be required to estimate situations where queues are so long that multiple green intervals are required before a vehicle in the queue is serviced.

RELIABILITY OF TRAVEL TIME

Reliability in travel time is an important aspect of the effectiveness of ASCT. Reliability measures have rarely been estimated in previous signal system evaluations. Figure 8 illustrates illustrates the potential improvements of a mitigation strategy that are ignored if the focus is only on the change to the average performance.

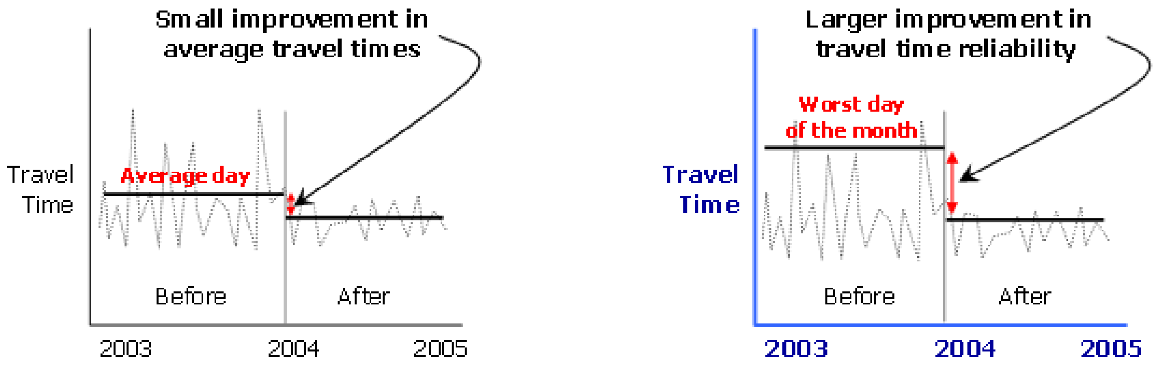


Figure 8. Illustration. Representation of the Value of Reliability Improvements.
(Source: Federal Highway Administration, 2008.)

The most effective methods of measuring travel time reliability are to use the 90th or 95th percentile travel times, buffer index, and planning time index, as explained in the following sections.

Several statistical measures, such as standard deviation and coefficient of variation might also be used. However, they treat early and late arrivals with equal weight. Assumptions of Normal distributions should not be used for this purpose as travel time performance is not symmetric with respect to the mean value. A Poisson or Beta distribution is more appropriate, but most standard statistical techniques applied in the literature use the assumptions of Normality.

90th or 95th Percentile Travel Times

Computing the 90th or 95th percentile travel time is perhaps the simplest method to measure travel time reliability. With enough observations, the value can be simply determined. With fewer observations, a statistical model is needed to predict what the 95th percent percentile value would be.

Buffer Time

The *buffer time* represents the extra time (or time cushion) that travelers must add to their average travel time to ensure on-time arrival. For example, a buffer index of 40 percent means that for a trip that usually takes 20 minutes a traveler should budget an additional eight minutes to ensure on-time arrival 95 percent of the time.

Average travel time = 20 minutes
Buffer index = 40 percent
Buffer time = 20 minutes × 0.40 = 8 minutes

The eight extra minutes is the buffer time. Therefore, the traveler should allow 28 minutes for the trip in order to ensure on-time arrival 95 percent of the time.

Planning Time

The *planning time* represents how much total time a traveler should allow to ensure on-time arrival. While the buffer time represents the additional travel time that is necessary, the planning time is just the *total* travel time that is necessary (see Figure 9).

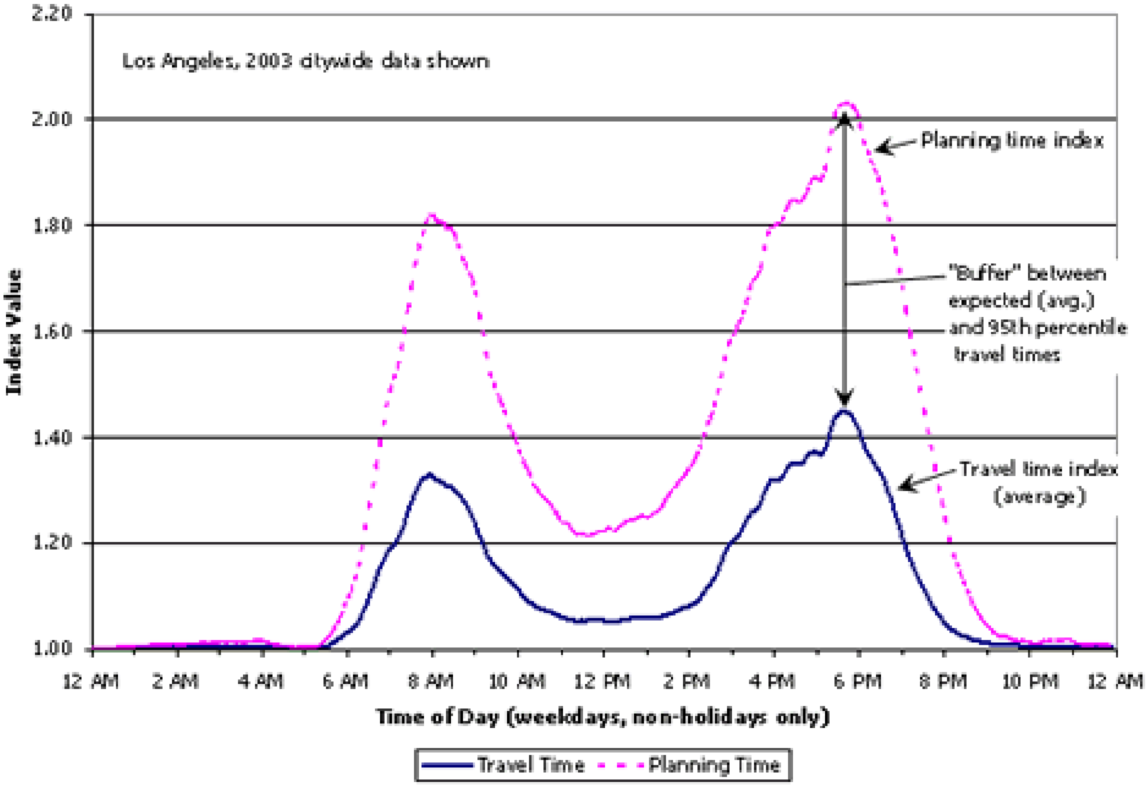


Figure 9. Illustration. Reliability Measures Compared to Average Congestion Measures. (Source: http://mobility.tamu.edu/mmp/.)

Reliability Indices

Both of these measures can also be expressed as indices to compare one route to another. For example, a planning time index of 1.60 means that for a trip that takes 15 minutes in light traffic a traveler should budget a total of 24 minutes to ensure on-time arrival 95 percent of the time.

Normal travel time = 15 minutes
Planning time index = 1.60
Planning time = 15 minutes × 1.60 = 24 minutes

The planning time index is especially useful because it can be directly compared to the travel time index on similar numeric scales. The travel time index measures the ratio of the difference between the best observed travel time and the average travel time.

Like percentages, these ratios can become nonsensical when the route distance or time is very short. If the normal travel time is four minutes but the 95 percent travel time is six minutes, the planning index is 1.5. Reporting and comparing ratios of this nature is always challenging. Figure 9 illustrates the relationship between the buffer index and the planning time index. The buffer index represents the additional time that is necessary, whereas the planning time index represents the total travel time that is necessary.

Reliability measures of travel time are derived from the base measurements and thus require no additional data collection systems or methods.

Reliability of Phase Performance

Reliability in travel time is an important aspect of the effectiveness of ASCT. Reliability in other measures is similarly important to measure changes in mitigation strategies. As illustrated previously, Figure 8 illustrates the potential improvements of a mitigation strategy that are ignored if the focus is only on the change to the average performance.

One metric that has been proposed to capture the reliability of phase performance is phase failures. A phase failure occurs when the traffic demand exceeds the green time for a phase resulting in an overflow queue that must be serviced in the following cycle. A control strategy that reduces the number and frequency of phase failure events would is considered more reliable. (Smaglik et al., 2006) describe simple diagnosis techniques from high-resolution phase and detector data for marking suspected phase failures, such as indicated by v/c ratios that are > 1.0 as illustrated in Figure 10.

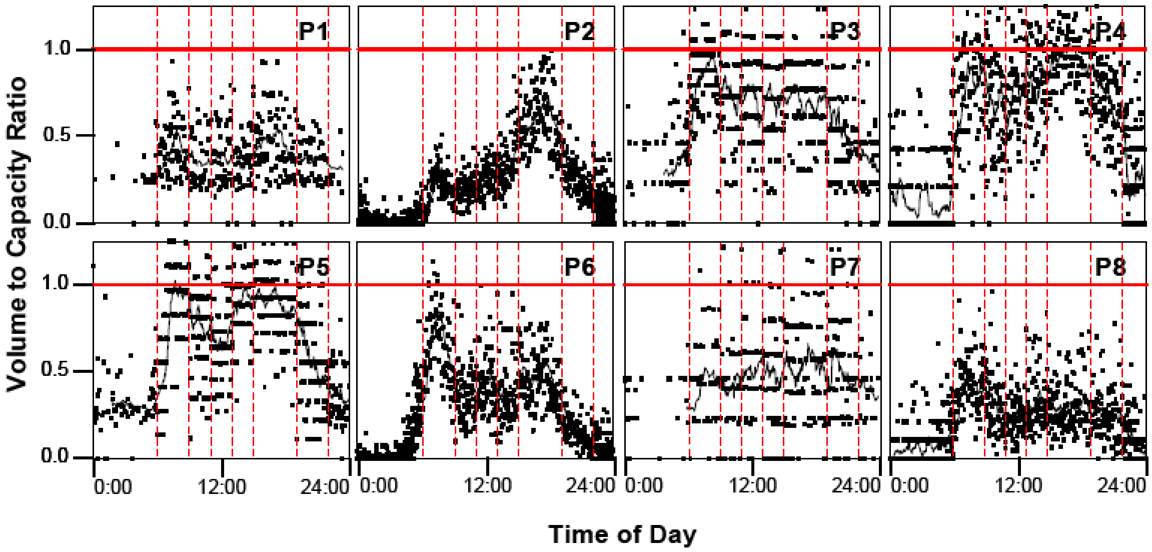
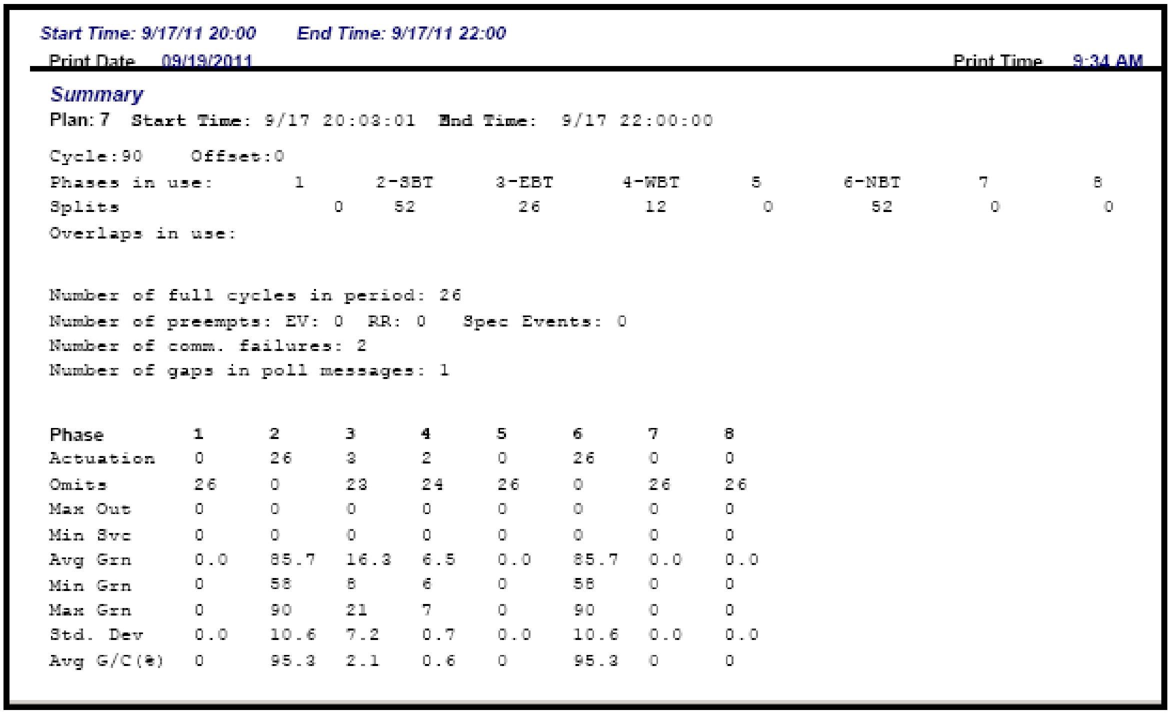


Figure 10. Scatter Graphs. V/C Ratio by Phase by Time of Day.
(Source: Bullock et al., 2008.)

Plots are helpful for humans to make decisions and assess comparative performance, but such displays must be translated into numbers for quantitative comparisons. Signal systems have long included split monitoring functions that tabulate average and variance of phase times for given time of day. Typical split monitor summary statistics are shown in Figure 11. Similar tabulation of v/c estimates and other metrics such as phase failures computed on a cycle-by-cycle basis could be used to compare the reliability of phase performance.



```
Start Time: 9/17/11 20:00      End Time: 9/17/11 22:00
 Print Date    09/19/2011                                                       Print Time    9:34 AM
 Summary
 Plan: 7  Start Time: 9/17 20:03:01  End Time:  9/17 22:00:00

 Cycle:90    Offset:0
 Phases in use:       1       2-SBT      3-EBT      4-WBT      5        6-NBT       7          8
 Splits                   0     52         26         12         0         52         0          0
 Overlaps in use:


 Number of full cycles in period: 26
 Number of preempts: EV: 0  RR: 0   Spec Events: 0
 Number of comm. failures: 2
 Number of gaps in poll messages: 1


 Phase        1      2      3      4      5      6      7      8
 Actuation    0      26     3      2      0      26     0      0
 Omits        26     0      23     24     26     0      26     26
 Max Out      0      0      0      0      0      0      0      0
 Min Svc      0      0      0      0      0      0      0      0
 Avg Grn      0.0    85.7   16.3   6.5    0.0    85.7   0.0    0.0
 Min Grn      0      58     8      6      0      58     0      0
 Max Grn      0      90     21     7      0      90     0      0
 Std. Dev     0.0    10.6   7.2    0.7    0.0    10.6   0.0    0.0
 Avg G/C(%)   0      95.3   2.1    0.6    0      95.3   0      0
```

Figure 11. Screen Shot. Example Split Monitoring Summary Statistics.
(Source: Miami-Dade County, FL signal system, 2011.)

DERIVED MOES

Impact on society and the public is also of importance in assessing the performance of ASCT against their operational objectives. Reduction in fuel use, emissions, and dollar-cost impact or benefit/cost ratio are typically used to estimate impacts on society. Most past studies include some discussion of these impacts to ensure that the system was a valuable investment. There are several assumptions that are necessary to convert from objective measurements such as travel time to societal impacts. While societal impact measures are valuable to estimate, they should not be used to compare the effectiveness or value of one system versus another.

Fuel Use

Fuel use for an individual trip can be computed from GPS probe vehicle trajectories using assumptions about vehicle make/model. Extrapolating individual probe performance to fleet impacts requires assumptions about the mixture of the fleet in a given locale, including the distribution of make/model/year/condition/environment and the percentage of trucks and other heavy vehicles.

Emissions

Emissions output for an individual trip can be computed from GPS probe vehicle trajectories using assumptions about vehicle make/model/condition/environment. A variety of tools are available, including MOBILE6, CMEM, MOVES, and VT-MICRO. Extrapolating individual probe performance (such as is done using CMEM) to fleet impacts requires assumptions about the mixture of the fleet in a given locale, including the distribution of make/model/year and the percentage of trucks and other heavy vehicles. Recent research has indicated that measurement of air quality impacts from changes in average speed is not reliable. Measurement of acceleration and deceleration due to stops is necessary for reliable characterization of emissions impacts.

Net Present Value and Benefit/Cost Ratios

It is an important justification of any project to show that the benefits of the project outweigh the costs of implementation. Such practice is common in transportation engineering. For example, The U.S. DOT TIGER grant process requires the computation of B/C ratio of any project according to sound economic principles including the computation of the Net Present Value of all anticipated impacts over a significant time period (e.g., 20 years). Estimates for societal impacts of ASCT can have significant bias due to assumptions on the price of fuel, value of time, and how benefits would continue to accrue due to the ASCT versus the "do nothing" alternative. In particular, most past studies neglect the fact that most agencies will retime signals on three- to five-year intervals. More research is necessary to develop a recommended practice for calculation of B/C ratios for ASCT deployment.

DOWN-SELECTION OF METRICS FOR ASSESSMENT OF OPERATIONAL OBJECTIVES

All of these MOEs cannot be implemented and tested in this project based on budget and schedule. The following methods summarized in Table 5 are proposed as the focus of this process as a proof of concept for validation of ASCT.

Table 6. Proposed MOEs for each Operational Objective.

Operational Objective	Proposed MOEs
Smooth flow	Route travel time, delay, average speed Link travel time, delay, average speed Traffic volume on route (throughput) Percent arrivals on green, by link Platoon ratio, by link Number of stops per mile on route

Table 6. Proposed MOEs for each Operational Objective.

Operational Objective	Proposed MOEs
Access equity	Phase green to occupancy ratio by movement V/C ratio by movement
Manage queues	Number of stops per mile on route
Changing objectives by TOD	Covered by MOEs from other objectives

These metrics can all be measured by collection of data using GPS probe vehicles, vehicle re-identification systems, high-resolution signal and detector data, and screen-line traffic volumes. Measurement of queues should be deferred at this time due to the technical complexity in implementation of the appropriate algorithms from available data sources. Similarly, prescription of methodology for calculation of derived measures such as fuel use, emissions, and B/C ratios should be deferred to future work.

CHAPTER 5. VALIDATION GUIDANCE

This project has developed tools and measures to assist agencies in satisfying the validation steps of the systems engineering process. This chapter summarizes the data and measures that address some of the operational objectives defined earlier. A few categories of important suggestions are then discussed for improving state of the practice in validation of agency operational objectives.

SUMMARY OF DATA AND MEASURES OF EFFECTIVENESS TO VALIDATE OPERATIONAL OBJECTIVES

This project has identified data and MOEs that can be used to validate some common signal operational objectives, both for ASCT operation and traditional signal timing. These measures and data sources are identified in Table 7.

Table 7. Identification of Data Sources and MOEs for each Operational Objective.

MOEs	Data Sources	Operational Objectives (FHWA-HOP-11-27, PG 94, References 3.4.4)
• Smooth flow	• Import travel time data from vehicle re-identification scanners • Import trajectory data from GPS probes • Import high-resolution signal timing and detector data	• Route travel time • Route travel delay • Route average speed • Link travel time, delay • Number of stops per mile on route • Percent arrivals on green, by link • Platoon ratio, by link
• Access Equity	• Import high-resolution signal timing and detector data	• Green-Occupancy-Ratio • Min, Max, and Std. Deviation of GOR • Served V/C ratio by movement • Min, Max, and Std. Deviation of GOR
• Throughput	• Import count data from tube counter file	• Total traffic volume on route • Time to process equivalent volume
• Travel time reliability	• Import travel time data from Bluetooth scanner • Import trajectory data from GPS probe • Import high-resolution signal timing and detector data	• Buffer time • Planning time • Min, Max, and Std Deviation of platoon ratio • Min, Max, and Std. Deviation of percent arrivals on green

Additional common objectives such as shifting objectives by time of day, long-term performance reliability, handling of incidents and events, preventing oversaturation, and managing queues may be extended from this project in future work.

SMOOTH FLOW OBJECTIVE

The smooth flow objective is perhaps the most commonly studied and validated operational objective in suburban settings. This objective can be addressed with vehicle re-identification systems, GPS probe runs, and occupancy data from advance detectors connected to the signal controller. As discussed previously, each data source has benefits and limitations for computing performance. Vehicle re-identification systems can provide a wealth of data 24x7, but only on the point to point travel time. GPS probe runs provide more detailed information on link-by-link performance and can more easily pinpoint trouble areas, but are expensive to collect in order to generate a large data set. MOEs from the signal controller produce link-by-link performance 24x7 and also efficiently identify trouble spots like probes, but new methods are needed to aggregate these data into information about the performance of a route; and many signal controllers aren't already equipped with such detection. The conduct of travel time studies and placement of detection is vital to obtain accurate validation results.

Configuration of Travel Time Routes and Conducting Travel Time Runs

The way that travel times are calculated is an important component of measuring a system's performance. In particular, it is important that travel time trips have several key components:

- GPS Probe trips must begin before the first intersection considered "in the system" and upstream of any typical queuing at that location during the red interval. This is particularly important since holding a significant queue at the first intersection (and even worse, one that experiences phase failures) can have the effect of artificially improving the travel time on the rest of the route. This gives a false impression of the quality of travel along the facility, whether operated by an ASCT or traditional control methods.
- GPS probe trips should end after clearing the last intersection considered "in the system". If the GPS probe application provided as part of this project is used for the data collection, the system will automatically discard any extra trip time past the last time point configured for the route, so drivers do not have to be as precise as to when they press the "stop" button after safely stopping their vehicle.
- Start of GPS probe trips should be randomized to have the first signal in both green and red phases an approximately equal amount of time, if enough trips can be executed within budgetary constraints. If not, all trips should start with the light being red for a random amount of time when the trip is started. Otherwise, as noted above, the queue delay at the first intersection is not captured in the reported performance.
- GPS probe trips need to follow the general speed of prevailing traffic. Drivers should behave as most drivers would, such as by passing slow-moving busses. If busses or other impediments are frequent and common along a route, however, those travel times should not be discarded in order to display only the best possible trips.

- Trips that occur during Oversaturation and events should not be immediately discarded. In particular, the occurrence of construction or other events that affect travel on a route for extended periods of time should be considered an opportunity to collect data during atypical situations, as discussed further in following sections.

Similarly, use of vehicle re-identification detectors for recording travel times requires careful placement and consideration of the range of the reader or placement of the detector, depending on the technology being applied. In the case of Bluetooth, most antennas provide a circular coverage zone which can result in initial identification of the vehicle on the exit side of the first intersection and/or re-identification of the vehicle on the entry side of the last intersection. This can skew the reporting of the travel times to exclude some of the queue delay in either or both situations. This phenomenon was demonstrated in this project since the Bluetooth travel times along Power Road were reported as significantly less than the travel times recording using the GPS probe method. Reliability estimates are also affected by excluding one or both of the queue delay conditions. If only one or the other method (i.e. either GPS probes or vehicle re-identification systems) is used in a validation effort, the comparative analysis of two or more operating conditions is not generally affected; but should be noted in the summary results. System vendors are aware of these issues and most are actively developing technologies and algorithms to improve their accuracy.

ACCESS EQUITY OBJECTIVE

Access equity is also a common operational objective. A balance between access equity and smooth flow operation is common in most suburban settings with some variation in agency and locality preferences. This objective can be addressed with detector occupancy and green time data from stop-bar detectors connected to the signal controller. The main challenge in many systems will be that some agencies do not utilize stop-bar detection for phases that are coordinated 24x7. If advance detection zones or loops are reasonably close to the stop bar, some anecdotal research indicates that GOR measures can be computed and compared with stop bar zones from side-street detectors at the stop bar. More research is needed to validate this further. Statistics (i.e. reliability) of the GOR and served V/C are also important metrics for determining the range of performance between operational strategies.

THROUGHPUT OBJECTIVE

Throughput on a route is an important objective for many agencies. Rather than simply counting total traffic volume, measuring the time it takes to process a given number of vehicles provides a better measure of the efficiency of the traffic system. This objective can be addressed fairly simply with tube counters or other traffic counting equipment (video, laser, etc.) deployed at a specific location. In addition, counting detectors connected to the signal controller can also be leveraged for this purpose given they are located far enough from the stop bar so that queues do not habitually form on top of those zones. Exit detection is particularly suited for counting vehicles when the distance to the next intersection is significant. Since data is taken at a specific point, this measure addresses both through traffic and turning traffic and does not directly reflect throughput on a specific route. Additional techniques using O-D synthesis and multiple counting points are needed to extract likely route flows.

TRAVEL TIME RELIABILITY OBJECTIVE

Reliability of system operation is receiving increased focus in recent years with a variety of research and development projects as part of the SHRP2 research program (http://www.trb.org/StrategicHighwayResearchProgram2SHRP2/Pages/Reliability-159.aspx). Travel time reliability can be measured using vehicle re-identification data, GPS probes, and detector occupancy data from advance detectors connected to the signal controller. For GPS probes and vehicle re-identification systems, buffer time is the primary measure of route reliability. Statistics of percent arrivals on green and platoon ratio can be computed from signal controller data to estimate reliability. As mentioned previously for the smooth flow objective, additional methods are needed to synthesize link-by-link statistics into reliability of performance along a route. Techniques for this type of data "fusion" are of high interest because they can reduce the cost of agency performance measurement significantly since no new field devices need to be deployed and expensive probe runs can be avoided (Although the advance or exit zones are still needed, which some agencies do not currently use). Vehicle re-identification systems pose a significant advantage for reliability estimation since they collect data 24x7.

IMPROVEMENTS TO VALIDATION PROCESSES

Validation of operational objectives is not an event but rather a process. The data collection and processing tools provided in this project can help extend the typical traditional "evaluation" study into a process of on-going performance measurement. Additional suggestions to improve state of the practice in validation of traffic signal operational objectives are provided in the following sub-sections.

Data Collection During Off-Peak Periods

Validating the performance of traffic signal operational objectives during peak-periods is, of course, critical since these are the most important times of operation of any traffic control strategy. As shown in the test case during this project, performance of a new mode of operation that does not significantly exceed the previous mode of operation in a peak period does not mean that the investment in the technology was wasted. Significant performance improvements are achievable during off-peak times, when traffic conditions can be more variable that the predictable and heaviest demands during the peak periods. When budgets are heavily constrained for validation efforts, it is not surprising that peak period data are collected first. Approaches demonstrated in this project such as deploying temporary (or permanent) Bluetooth detectors or using the data collected by the traffic controllers directly can help to reduce the effort involved in analyzing and reporting performance during off-peak times.

Validation of Objectives Instead of Comparison with Existing Operations

Management of expectations is an important component of deploying and implementing any new technology. ASCT is particularly challenging in this regard since it carries a certain expectation from the decision-makers and the general public that traffic congestion will be magically wiped away. When the investment cannot be shown to improve operations by X% over the previous type of traffic control, in many cases a poor light is cast on the technology investment. The history of past validation and evaluation approaches also muddy the waters because often they either (a) intentionally make the "before" case as poor as possible or (b) intentionally make the "before" case as good as possible or even (c) update the signal timings to be as good as possible and then apply ASCT on top of the improved timings. Since most people are accustomed to discussing performance with respect to percentages, it is no wonder why there is uncertainty about the relative benefits of one technology versus another.

In this project we took some steps towards providing MOEs that could independently assess the performance of a traffic control strategy, without having to compare the strategy against something else; however, much more work is still needed to develop higher level performance objectives that combine measurements at multiple intersections and along routes to validate that a particular strategy is meeting the agency's objectives for deployment. Such measures need to be objective ones, similar to the scores assigned by the HCM methods.

While it is probably unrealistic to expect that a validation methodology can be created that will eliminate the need for comparisons with a "before" condition, our guidance is that validation teams should at least consider explaining the quality of the timing parameters and operation in the before condition to identify where the problem areas lie as well as to identify where the operation is already acceptable.

Consideration of More Traditional Engineering Modifications that Cost Less

As noted in the preceding section, in the process of deploying ASCT it is common that "easy" fixes are identified for certain situations that really don't require an ASCT. These fixes might require simple updates to signal timing parameters such as splits, offset, or sequence; repair of broken detectors; or providing a reliable time source to keep clocks synced on an arterial. These kinds of basic traffic engineering fixes cost a fraction of the deployment cost of an ASCT; however, these fixes may just create a need to perform additional tweaks in two weeks or two months. The value of ASCT, in that it continually re-optimizes settings, is unquestioned. The challenge is that the validation work is typically executed shortly after the installation of the ASCT, and the benefits measured at that time might just as easily been achieved by simpler, much less expensive investments.

Before launching into an investment in ASCT, agencies might also consider a program of check-ups by qualified personnel on a more frequent basis than the typical "once every three years" cycle that is common in the industry. Perhaps the MOE and data collection techniques developed and provided in this project can help agencies determine when their own staff needs to make those modifications. Some agencies may find, however, that the investment in ASCT systems is invaluable since the operations are continually being optimized and agency staff can focus efforts on their other public works duties, which might vary substantially on any given day.

Consider an ON and OFF Study

Traditional "before" and "after" validation processes present a host of challenges to the comparison of one traffic operations approach with another. The further apart in time that the before and after data are collected, the larger the potential discrepancy between the traffic patterns becomes. This is typically accompanied by an additional effort to validate using volume counters that the two traffic conditions were the same. If the two conditions are not statistically similar, the comparison of results becomes quite difficult to explain. An ON and OFF process mitigates some of this problem since it is not typical that traffic patterns vary significantly from day to day, as long as the number of ON and OFF days for each day of the week are approximately the same. We propose that ON and OFF testing during the deployment phase of an ASCT or new signal timing strategy should be adopted as a best practice whenever practicable.

There is considerable (and understandable) political push-back to turn "OFF" an ASCT (or change the timings back to the previous settings) that has been running for some time in order to validate its operation since the common perception is that the agency is intentionally making things worse. This dovetails with the identified need to develop standards for MOE performance that can validate system operation without the need to turn "OFF" the system at all. This is an important area of recommended future research and development, as identified in other sections of this report.

Consider Measurement of Failure Modes and Incident Conditions

Atypical traffic conditions and system component failures are elements of technology deployment that occur in the real world. ASCT systems by their very nature are better suited to handle anomalous traffic conditions than traffic operations strategies that operate with fixed parameters. Similar to the political concerns over ON and OFF approaches, there is frequent concern about the reporting of performance during incident conditions or the inducement of incident conditions through artificial means (e.g., traffic cones, staged lane blockages, etc.). If more objective MOE definitions can be identified that can assess ASCT performance during atypical conditions, it may not be necessary to intentionally create incidents and then turn the system "OFF" as well, in order to see how bad it really gets. If possible, planners should try to use the data collected during real incidents in a meaningful manner. Performance results should probably be excluded from the calculations for MOE averages, but there is important information in the way the system reacts to the situation that should not just be discarded. At minimum, simply observing the modifications made by the system is important information about how the ASCT is attempting to address the situation. This is also an important recommended area for future research and development since it was not studied in detail in this validation project.

From the perspective of component failures, it is absolutely essential to identify what is going to happen when one or more ASCT components is off-line. Does this system fail "free"? Does it go back to coordinated operation? With what coordination parameters? Worst of all, some ASCT systems can get "stuck" in certain phases of signal indications for extended periods of time or induce signal flash. These situations (which can also be created by traditional signal operations), are to be avoided at all costs since they generate phone calls at an extraordinary rate and mobility performance is damaged significantly. Testing and validation that the ASCT fails to generate an appropriate type of operation should be a central component of any validation study. This is particularly important when deploying any system that includes a new type of control method, a new controller interface, an "upgraded" piece of hardware or firmware, a new detector type, or anything else that has not been sufficiently proven elsewhere.

Consider a Longer-Term Program of Performance Monitoring

The value of ASCT systems and managing traffic signal operations to performance objectives lies not only in the initial impacts but in its long-term function of continuing to adapt to changing traffic patterns over months and years. We recommend that if possible, agencies treat the validation step as a program of continual, or at least periodic, activities, rather than a singular event. In signal system deployments, there are typically two components of the systems engineering process: the acceptance test, which verifies that the procured features are available and function as intended, and the "burn in" period where the operation is checked for several months to identify if any systemic issues arise due to the passing of time. A similar approach is recommended here, but extended much further into the future. The measures and tools provided in this project can help enhance the ability to conduct "check-ups" over time. This recommendation is in line with the over-arching goal of MAP-21 to move agencies towards on-going performance measurement as part the core mission of traffic management agencies.

CHAPTER 6. FUTURE RESEARCH AND DEVELOPMENT

This project has resulted in an open-source, web-based system for ingesting data from four sources of signal performance data and computing performance metrics and comparing performance for different conditions in order to validate that ASCT systems meet their operational objectives. The system produces comparative results, but does not generate conclusions about validity. Human analysts are still a necessary component of the process in many ways to process the data, interpret the findings, and generate reports. At minimum, future research and development is needed to identify higher-level quantitative metrics that map directly to certain operational objectives for direct validation, similar to the way HCM methods classify system performance on an A-F scale.

For example, the access equity objective generally requires that the green time allocated for each phase is appropriate for the demand—that the movement is provided enough green to process all vehicles waiting during the red phase, and not too much more. The red time for each phase is not unduly long, and particularly during red, the waiting vehicles do not perceive that other green time is being wasted when no vehicles are being serviced through the intersection. Using the GOR measure, for example, this qualitative goal might manifest itself as a metric to provide GOR values for all phases at the intersection as close to 80% as possible. Other target percentages might be selected. Other researchers (Zheng, et al., 2012) have suggested that perhaps an appropriate target for access equity is Webster splits.

For smooth flow operation, the objective is principally to drive the number of stops on the arterial route as close to zero as possible. Objective targets for the number of stops per mile and the average speed for various facility types need to be established similar to the way the HCM methods establish arterial performance from estimates of the various parameters. Research and development is needed to determine if the real-time, calculated components for platoon ratio and the other inputs to the HCM delay equations can be used for this purpose. In addition, metrics might be established from percent arrivals on green such as the following: "if the percent arrivals on green on an arterial route are greater than 75%, 80% of the time, then a smooth flow objective is validated". Some areas of the country denote this kind of quantitative objective in a qualitative way as "maximizing the greens to reds ratio", which is equivalent to driving the number of stops on the route as low as possible.

For queue management, the missing piece is obviously the measurement of queue lengths. Techniques are available in the literature (Liu, et al., 2009; 2011) to leverage advance detection zones for this. It is recommended that this method be incorporated or other similar methods be developed into the MOE calculation engines. Once these calculations are available, higher level quantitative metrics will be required that identify a traffic control system's ability to meet this objective.

As an open-source project, we hope that researchers will extend the system in various ways noted above, and in ways we have not envisioned, and pass these improvements back to the open-source project for the betterment of all. The project is posted at https://sourceforge.net/projects/fhwaasctvalidat/.

CHAPTER 7. REFERENCES

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CHAPTER 8. LITERATURE REVIEW

The literature review is a summary of literature from agencies, consultants, and academics and is not intended to be comprehensive. Many studies are repetitive and consider the same MOEs and methodology and apply the techniques to different locations. The review also focuses on recent studies that consider unique MOEs, and studies that articulate objectives. It has not been common for studies to focus on *validation* of *objectives* but rather to evaluate the improvements provided by an ASCT over the previous signal timings. The intention of the review is to identify best practices, common flaws, and emerging trends and in order to develop a recommended practice for *validation*.

ROUTE TRAVEL TIMES AND STOPS

Collecting route travel time data is the most common evaluation approach for traffic studies. Travel time is collected using a variety of means and is a direct measure of how well the traffic flow is for the arterial. In most studies, multiple "probes" travel the corridor collecting start time, time at which each signalized intersection is encountered, and the time to reach the stopping point of the corridor. The test car technique is described well in the Institute of Transportation Engineers Manual of Transportation Engineering Studies.[1] For these types of studies, the test car (probe) is driven at the posted speed limit unless impeded by traffic conditions. This methodology is also sometimes referred to as a "floating car" study as drivers are instructed to "pass as many cars as being passed by." Turner (1998) developed a complete methodology for FHWA using the techniques common to the industry at that time.[2] Each of these techniques has been perfected over the years and a variety of new devices are now available for measurement of travel times using GPS probes and vehicle re-identification methods. Figure 12 illustrates a typical exhibit for comparing before and after performance.

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[1] H.D. Robertson, J.E. Hummer, and D.C. Nelson. *Manual of Transportation Engineering Studies*. Institute of Transportation Engineers. Prentice-Hall, Englewood Cliffs, NJ. 1994.

[2] *Travel Time Data Collection Handbook.*

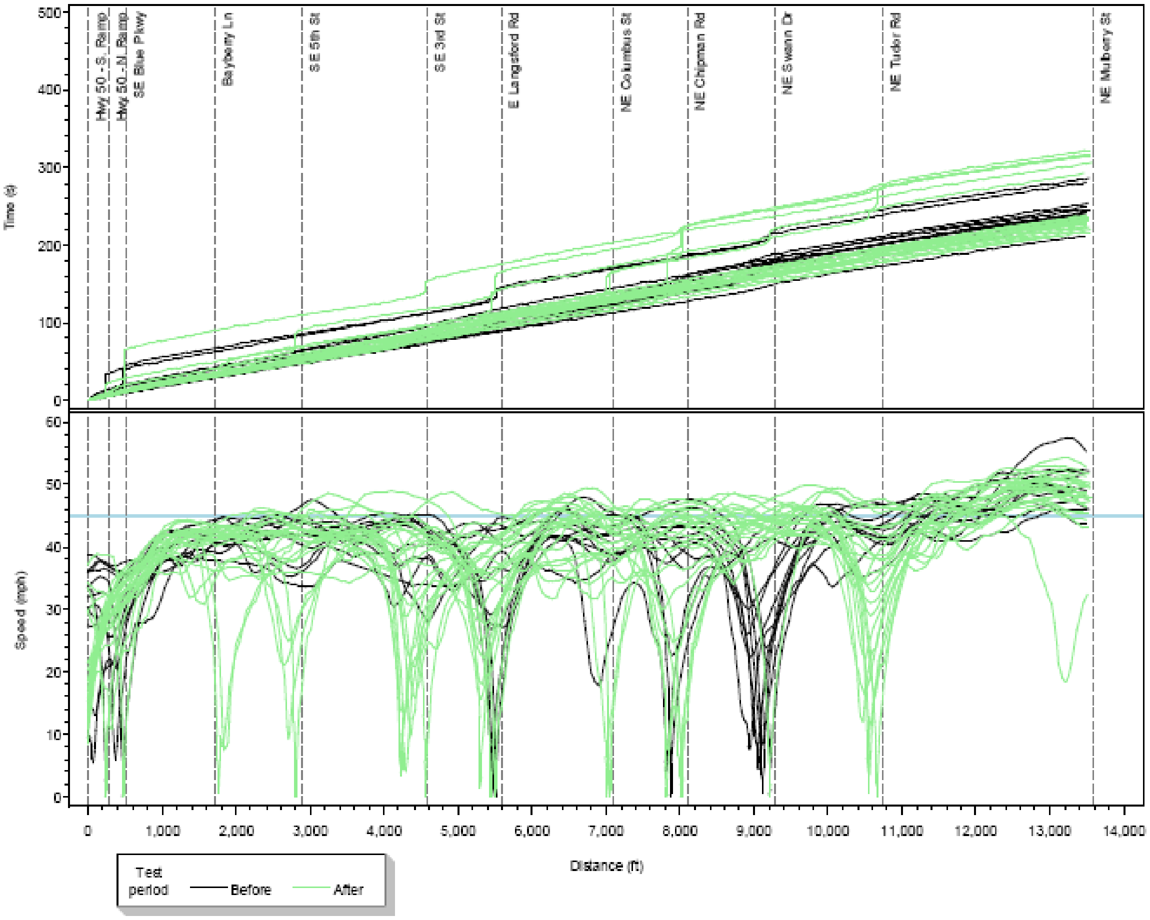

Figure 12. Illustration. Example of Speed Versus Distance and Time-Space Diagram Displays in Studies
(Source: MoDOT, 2010.)

The collection of travel time data using probes requires a careful consideration of the number of travel runs necessary to be considered statistically significant. The NCHRP Report 398[3] is typically used to identify the suggested sample size for data collection on arterial streets. The recommended approach considers the standard normal variation based on the desired confidence level, coefficient of variation of travel times (percent), and specified relative error (percent). Some studies identified in the literature go through the calculations for the number of travel time runs but the vast majority of methods pick a "reasonable" number of runs which might be between 2 to 15 for a given travel direction. Because probe data has historically been expensive to collect (requiring a driver and a passenger), the data collection is limited by project budget. These relatively low numbers of runs can be used to compare averages, but are not effective in assessing improvements to travel time *reliability* that may result from application of ASCT. In addition, travel-time varies with traffic volume. Studies that consider this effect such as (Fehon

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[3] National Cooperative Highway Research Program. *Quantifying Congestion. Volume 1 – Final Report*. NCHRP 398. Transportation Research Board, 1997, Washington, D.C.

et al., 2010) multiply the average travel time recorded by probe runs by the traffic volume recorded at that time of day to estimate the total vehicle travel time on that route. Further, they weight directional results by distance to combine multiple directions to achieve a plot such as illustrated in Figure 13. Similarly, total stops can be estimated from a similar procedure using the probe data.

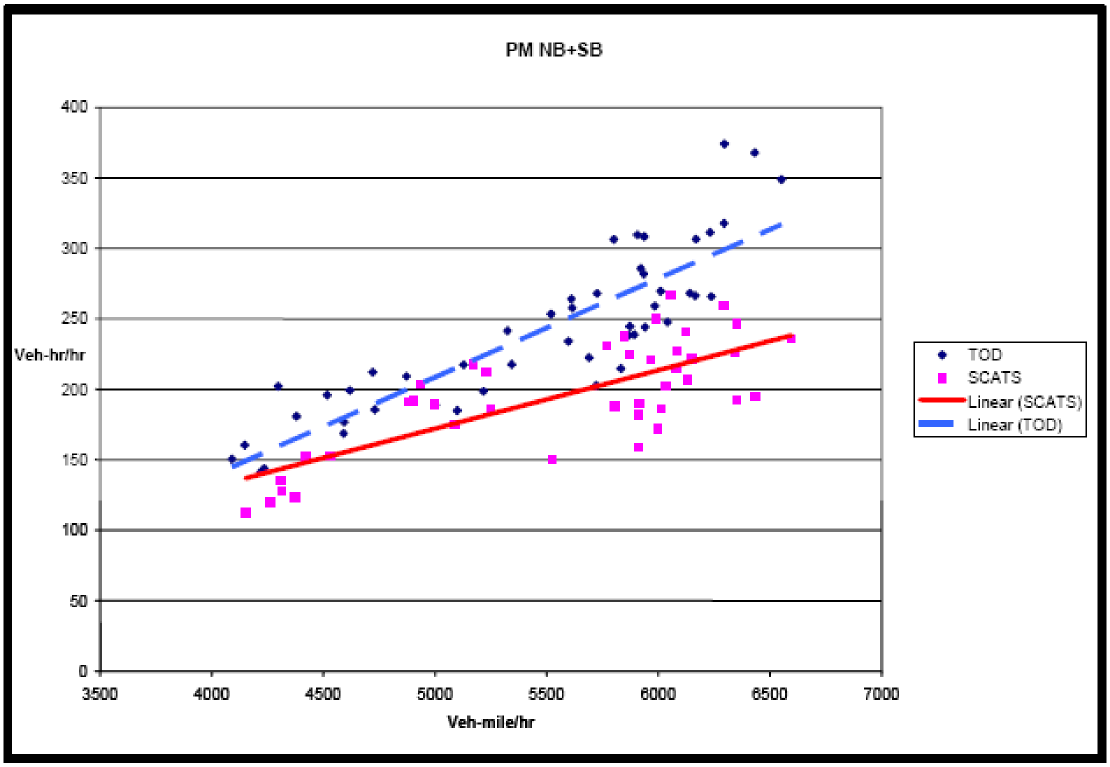
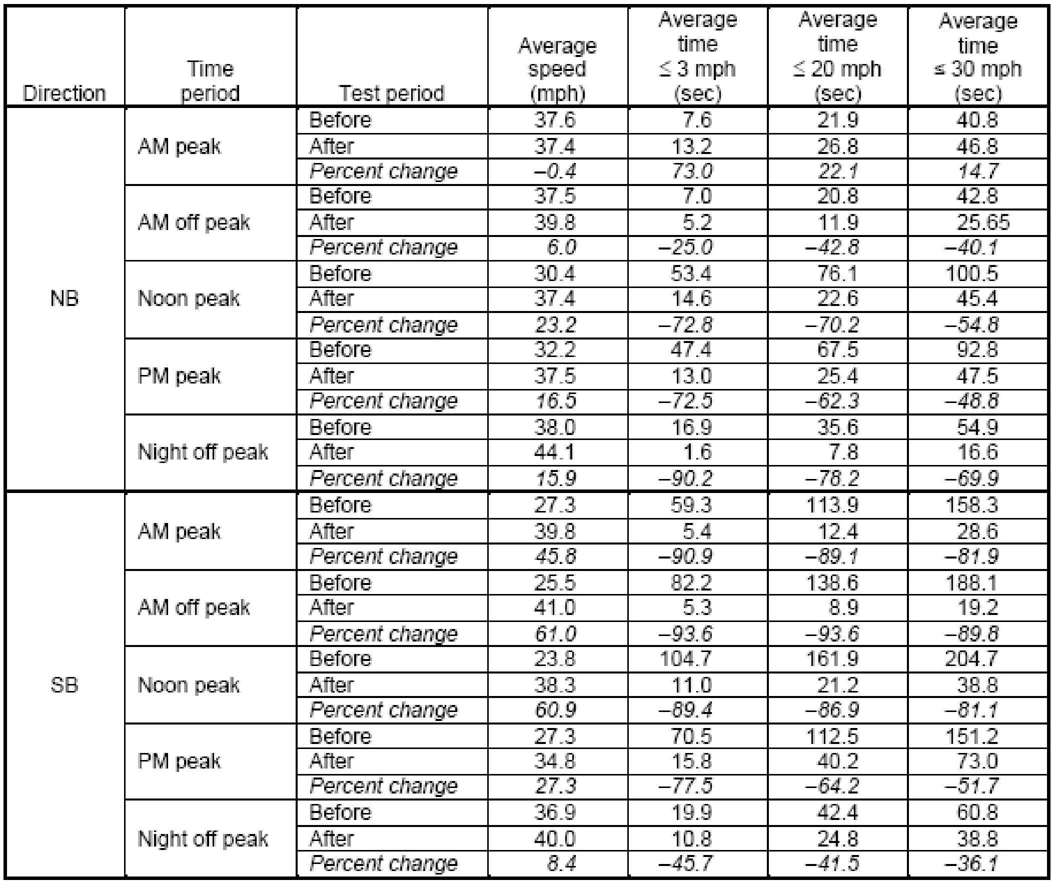


Figure 13. Line Graph. Example Comparison of Volume and Distance-Weighted "Total System" Travel Times
(Source: Fehon, 2010.)

Another approach to reporting performance has been to identify the amount of time spent in "congestion" conditions (Midwest Research, 2010) based on an average speed assumption. In this study time spent traveling at average speed less than 20 mph was defined as congested. An example summary table is shown in Figure 14.



Direction	Time period	Test period	Average speed (mph)	Average time ≤ 3 mph (sec)	Average time ≤ 20 mph (sec)	Average time ≤ 30 mph (sec)
NB	AM peak	Before	37.6	7.6	21.9	40.8
		After	37.4	13.2	26.8	46.8
		Percent change	*−0.4*	*73.0*	*22.1*	*14.7*
	AM off peak	Before	37.5	7.0	20.8	42.8
		After	39.8	5.2	11.9	25.65
		Percent change	*6.0*	*−25.0*	*−42.8*	*−40.1*
	Noon peak	Before	30.4	53.4	76.1	100.5
		After	37.4	14.6	22.6	45.4
		Percent change	*23.2*	*−72.8*	*−70.2*	*−54.8*
	PM peak	Before	32.2	47.4	67.5	92.8
		After	37.5	13.0	25.4	47.5
		Percent change	*16.5*	*−72.5*	*−62.3*	*−48.8*
	Night off peak	Before	38.0	16.9	35.6	54.9
		After	44.1	1.6	7.8	16.6
		Percent change	*15.9*	*−90.2*	*−78.2*	*−69.9*
SB	AM peak	Before	27.3	59.3	113.9	158.3
		After	39.8	5.4	12.4	28.6
		Percent change	*45.8*	*−90.9*	*−89.1*	*−81.9*
	AM off peak	Before	25.5	82.2	138.6	188.1
		After	41.0	5.3	8.9	19.2
		Percent change	*61.0*	*−93.6*	*−93.6*	*−89.8*
	Noon peak	Before	23.8	104.7	161.9	204.7
		After	38.3	11.0	21.2	38.8
		Percent change	*60.9*	*−89.4*	*−86.9*	*−81.1*
	PM peak	Before	27.3	70.5	112.5	151.2
		After	34.8	15.8	40.2	73.0
		Percent change	*27.3*	*−77.5*	*−64.2*	*−51.7*
	Night off peak	Before	36.9	19.9	42.4	60.8
		After	40.0	10.8	24.8	38.8
		Percent change	*8.4*	*−45.7*	*−41.5*	*−36.1*

Figure 14. Table. Example of Results Reported as Time Spent in Congested Conditions.
(Source: Midwest Research, 2010.)

Many studies report only arterial end-to-end travel times and neglect collection of data on routes that have different origins and destinations in the system and combinations of turning movements. Only a limited number of studies have considered multiple network paths (Hunter et al., 2005). When probe vehicles are used, most studies report average stops and use graphics to depict differences between before and after conditions. An effective graphic for comparing travel times by time of day is illustrated in Figure 15.

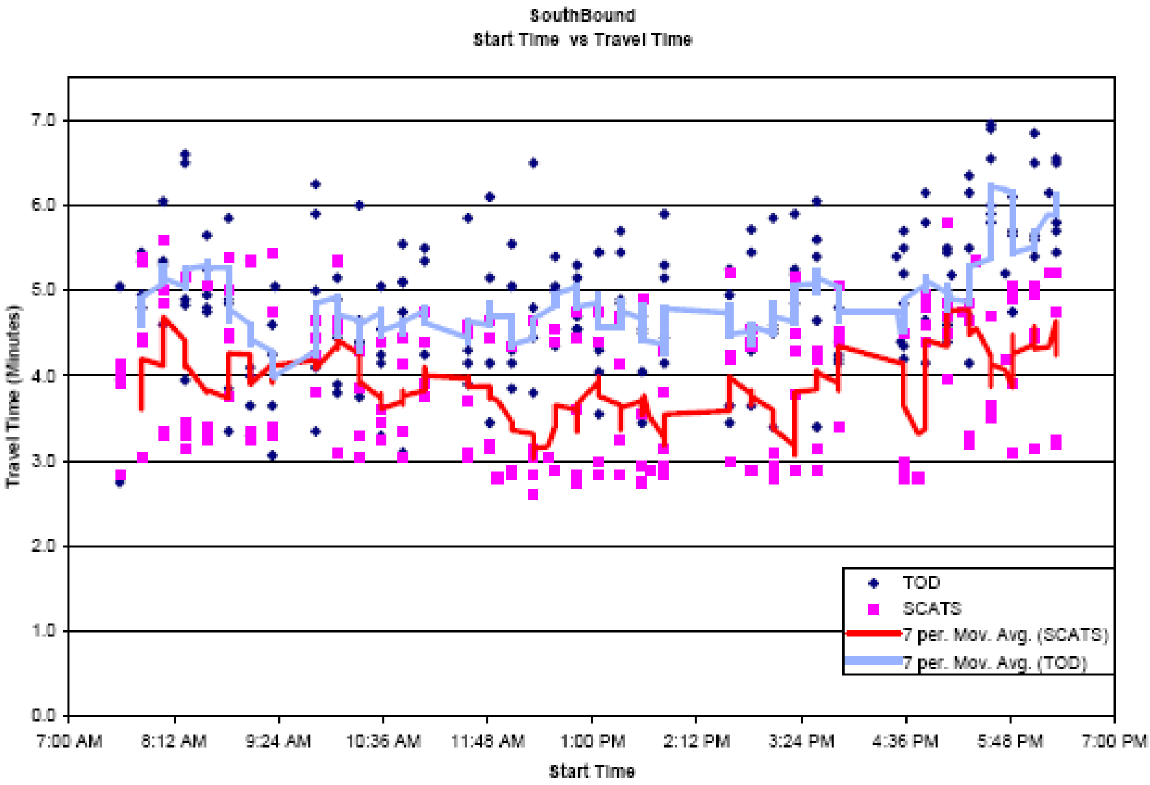
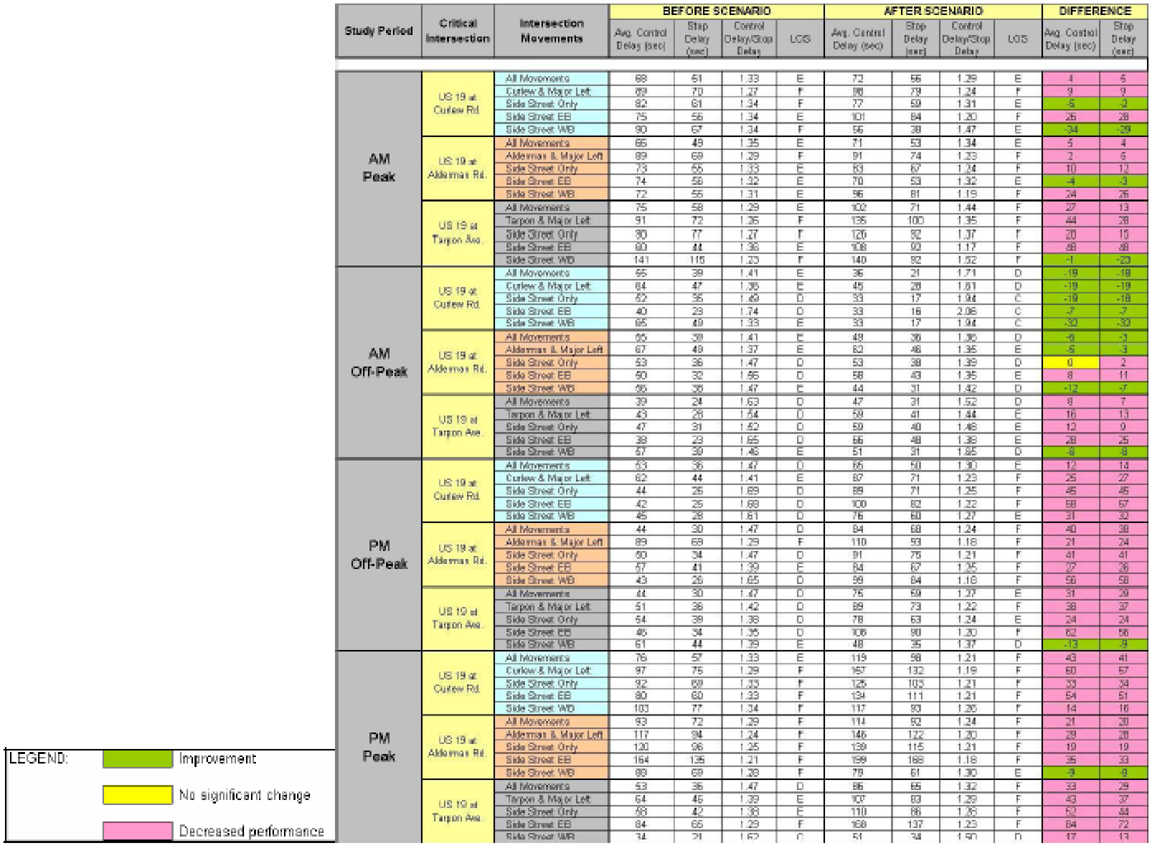


Figure 15. Line Graph. Example Comparison of Travel Times by Time of Day
(Source: Midwest Research, 2010.)

When vehicle re-identification technologies are used instead of probe vehicles, stops cannot be computed, so reductions or changes in delay and travel time are only typically reported.

SIDE-STREET PERFORMANCE

Most studies augment route travel times with collection of a limited amount of side-street performance data using traditional manual observation techniques – counting vehicle queues and estimating delays. Due to the manual labor involved, all studies are limited in the duration of the data collection due to project budget. For example, Wetzel et al. (2011) used the procedures found in the 2010 HCM to evaluate an ASCT system in Seminole County, Florida. A survey period of 30 minutes was used. Survey data collection started at the beginning of the red indication for the study lane group when no vehicles were queued. The field personnel recorded vehicle arrivals, and the number of vehicles in the queue (Queue-count). Vehicle arrivals were classified as “stopped” or “nonstopped.” Vehicles turning right-on-red that did not significantly yield to conflicting traffic were recorded as “not-stopped.” Pedestrian delay is typically measured using a stopwatch technique. Delay was measured from the moment a pedestrian arrived at the intersection until they entered the roadway and started to cross the street. An example exhibit on side-street comparison performance is shown in Figure 16.



Study Period	Critical Intersection	Intersection Movements	BEFORE SCENARIO				AFTER SCENARIO				DIFFERENCE	
			Avg. Control Delay (sec)	Stop Delay (sec)	Control Delay/Stop Delay	LOS	Avg. Control Delay (sec)	Stop Delay (sec)	Control Delay/Stop Delay	LOS	Avg. Control Delay (sec)	Stop Delay (sec)
AM Peak	US 19 at Curlew Rd.	All Movements	68	51	1.33	E	72	56	1.29	E	4	5
		Curlew & Major Left	89	70	1.27	F	98	79	1.24	F	9	9
		Side Street Only	82	61	1.34	F	77	59	1.31	E	-5	-2
		Side Street EB	75	56	1.34	E	101	84	1.20	F	26	28
		Side Street WB	90	67	1.34	F	56	38	1.47	E	-34	-29
	US 19 at Aldermas Rd.	All Movements	66	49	1.35	E	71	53	1.34	E	5	4
		Aldermas & Major Left	89	69	1.29	F	91	74	1.23	F	2	5
		Side Street Only	73	55	1.33	E	83	67	1.24	F	10	12
		Side Street EB	74	56	1.32	E	70	53	1.32	E	-4	-3
		Side Street WB	72	55	1.31	E	96	81	1.19	F	24	26
	US 19 at Tarpon Ave.	All Movements	75	58	1.29	E	102	71	1.44	F	27	13
		Tarpon & Major Left	91	72	1.26	F	135	100	1.35	F	44	28
		Side Street Only	90	77	1.27	F	120	92	1.37	F	20	15
		Side Street EB	60	44	1.36	E	108	92	1.17	F	48	48
		Side Street WB	141	115	1.23	F	140	92	1.52	F	-1	-23
AM Off-Peak	US 19 at Curlew Rd.	All Movements	55	39	1.41	E	36	21	1.71	D	-19	-18
		Curlew & Major Left	64	47	1.36	E	45	28	1.61	D	-18	-19
		Side Street Only	52	35	1.49	D	33	17	1.94	C	-19	-18
		Side Street EB	40	23	1.74	D	33	16	2.06	C	-7	-7
		Side Street WB	65	49	1.33	E	33	17	1.94	C	-32	-32
	US 19 at Aldermas Rd.	All Movements	55	39	1.41	E	49	36	1.36	D	-6	-3
		Aldermas & Major Left	67	49	1.37	E	62	46	1.35	E	-5	-3
		Side Street Only	53	36	1.47	D	53	38	1.39	D	0	2
		Side Street EB	50	32	1.56	D	58	43	1.35	E	8	11
		Side Street WB	56	38	1.47	E	44	31	1.42	D	-12	-7
	US 19 at Tarpon Ave.	All Movements	39	24	1.63	D	47	31	1.52	D	8	7
		Tarpon & Major Left	43	28	1.54	D	59	41	1.44	E	16	13
		Side Street Only	47	31	1.52	D	59	40	1.48	E	12	9
		Side Street EB	38	23	1.65	D	66	48	1.38	E	28	25
		Side Street WB	57	39	1.48	E	51	31	1.65	D	-6	-8
PM Off-Peak	US 19 at Curlew Rd.	All Movements	53	36	1.47	D	65	50	1.30	E	12	14
		Curlew & Major Left	62	44	1.41	E	87	71	1.23	F	25	27
		Side Street Only	44	26	1.69	D	89	71	1.25	F	45	45
		Side Street EB	42	25	1.68	D	100	82	1.22	F	58	57
		Side Street WB	45	28	1.61	D	76	60	1.27	E	31	32
	US 19 at Aldermas Rd.	All Movements	44	30	1.47	D	84	68	1.24	F	40	38
		Aldermas & Major Left	89	69	1.29	F	110	93	1.18	F	21	24
		Side Street Only	50	34	1.47	D	91	75	1.21	F	41	41
		Side Street EB	57	41	1.39	E	84	67	1.25	F	27	26
		Side Street WB	43	26	1.65	D	99	84	1.18	F	56	58
	US 19 at Tarpon Ave.	All Movements	44	30	1.47	D	75	59	1.27	E	31	29
		Tarpon & Major Left	51	36	1.42	D	89	73	1.22	F	38	37
		Side Street Only	54	39	1.38	D	78	63	1.24	E	24	24
		Side Street EB	46	34	1.35	D	108	90	1.20	F	62	56
		Side Street WB	61	44	1.39	E	48	35	1.37	D	-13	-9
PM Peak	US 19 at Curlew Rd.	All Movements	76	57	1.33	E	119	98	1.21	F	43	41
		Curlew & Major Left	97	75	1.29	F	157	132	1.19	F	60	57
		Side Street Only	92	69	1.33	F	125	103	1.21	F	33	34
		Side Street EB	80	60	1.33	F	134	111	1.21	F	54	51
		Side Street WB	103	77	1.34	F	117	93	1.26	F	14	16
	US 19 at Aldermas Rd.	All Movements	93	72	1.29	F	114	92	1.24	F	21	20
		Aldermas & Major Left	117	94	1.24	F	146	122	1.20	F	29	28
		Side Street Only	120	96	1.25	F	139	115	1.21	F	19	19
		Side Street EB	164	135	1.21	F	199	168	1.18	F	35	33
		Side Street WB	88	69	1.28	F	79	61	1.30	E	-9	-8
	US 19 at Tarpon Ave.	All Movements	53	36	1.47	D	86	65	1.32	F	33	29
		Tarpon & Major Left	64	45	1.39	E	107	83	1.29	F	43	37
		Side Street Only	58	42	1.38	E	110	86	1.28	F	52	44
		Side Street EB	84	65	1.29	F	168	137	1.23	F	84	72
		Side Street WB	34	21	1.62	C	51	34	1.50	D	17	13

LEGEND:	
🟩	Improvement
🟨	No significant change
🟥	Decreased performance

Figure 16. Exhibit. Example of Side-Street Performance Summary.
(Source: Pinellas County, Florida, 2007.)

These simple techniques are effective, but just cannot be used for long periods of time due to cost. Human observers contribute errors to the process due to potential inattention and the real needs to take mental and physical breaks. Videotaping locations is also frequently used to reduce the need for on-site observers, but still the amount of information that can be distilled is limited by human-in-the-loop issues. High-resolution phase timing and detection data that is now becoming available from controllers, ASCT, and other signal systems can be used to reduce the manual effort to collect such measures as will be discussed further in this report.

Studies that report queue lengths as performance measures are almost always counted manually with observers. NCHRP 3-79 recommends use of videotaping and manual post processing. A few vendor technologies are emerging that claim the capability to count turning movements and queue lengths automatically from video cameras images. Such systems have not been evaluated and validated extensively enough to consider such automated methods as part of this process at this time.

BEFORE AND AFTER FORMAT

Almost all studies approach the data collection efforts in a “before” and “after” format. Fehon (2010)[4] has identified the inherent problems with traditional before and after smooth flow flow studies (specifically travel time surveys). He noted that the sample sizes are based on performance measures that compare mean values and are not intended to provide a basis for comparing measures of variability in travel times. In addition, before and after studies assume an underlying stability in the traffic conditions during the survey period, which may not be the case. In particular, studies neglect the collection of measures that reflect the ASCT capabilities to modify its operation to efficiently accommodate variations. It was concluded that traditional studies offer under-report the benefits of adaptive systems, and the conclusions drawn from those studies are unreliable.

Fehon (2010) has recently studied ASCT in Walnut Creek, California using a comprehensive performance evaluation. The use of Bluetooth devices were used to collect travel time data over 24 hours per day for two weeks, providing equal sample sizes for both “with” and “without” adaptive conditions. Fehon (2010) has also recently studied ASCT systems in Sunnyvale, California, and Santa Clara County, California. In these studies, the researchers collected travel time data and matched it to volume data measured at the same time, using 15-minute time slices, giving a single statistic of the total corridor performance for each time slice. All of the data points derived for the two weeks of surveys were analyzed and plotted in such a way that it was possible to clearly separate the effects of different volume levels.

It is not uncommon to collect the “before” conditions and “after” conditions with several months of time in between the two studies. Over this time, travel demand can, and typically does change due to a variety of reasons, such as site development and seasonal changes. This variability is often mitigated by collecting data on the same days of the week and within a given season. School schedules are typically accommodated in most studies due to the known changes in travel demand.

ON/OFF FORMAT

To get around the issues related to before/after studies, several studies have begun to study performance using on/off techniques. A study performed in Seminole County[5], Florida analyzed the green time utilization with the system active (“on”) and while it was inactive (“off”). In this case, the floating car technique was used. The probe vehicle began travel time runs at various time points during signal cycles or periods to avoid starting each run at the same location within a platoon. Stevanovic et al. has also applied some on/off techniques in simulation studies (2009) and Fehon recently applied the ON/OFF approach to evaluation as well (2010).

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[4] *Adaptive Traffic Signals, Comparison and Case Studies*. Fehon and Peters, 2010.

[5] SynchroGreen Real-Time Adaptive Traffic Control System: Seminole County SR 436 Deployment, 2011.

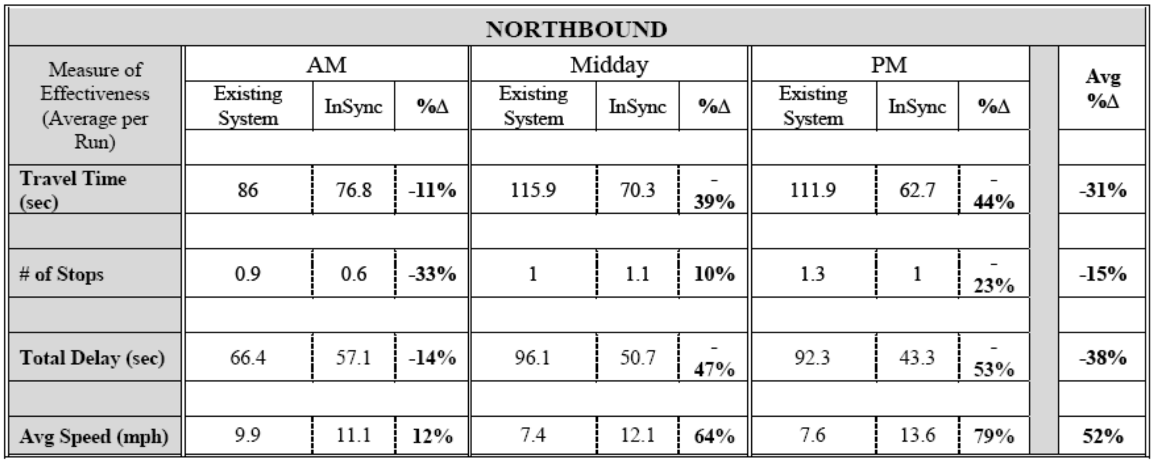
While an ON/OFF approach may be more defensible scientifically because comparisons have a stronger probability of having similar traffic conditions with the system on and off, such a study is more difficult to support politically by the agency owners. Laypeople and nontechnical stakeholders frequently view the intentional disabling of a technology as imprudent, particularly when the ASCT technology is a relatively expensive project with limited visible products (i.e., unlike construction).

QUALITY OF "BEFORE" TIMINGS

The largest contributor to the uncertainty about the benefits of ASCT is due to the quality of timings that the system is compared to. Some reports of hugely successful deployments (90 percent reductions in stops, etc.) have simply compared the ASCT to poorly configured or significantly outdated timings. Other studies report only modest improvements due to ASCT when compared to recently optimized timings or timings that are largely suitable for typical conditions. Both situations are accurate assessments of ASCT value, but tend to distort comparisons between systems when they are used inappropriately for decision-making.

REPORTING OF RESULTS

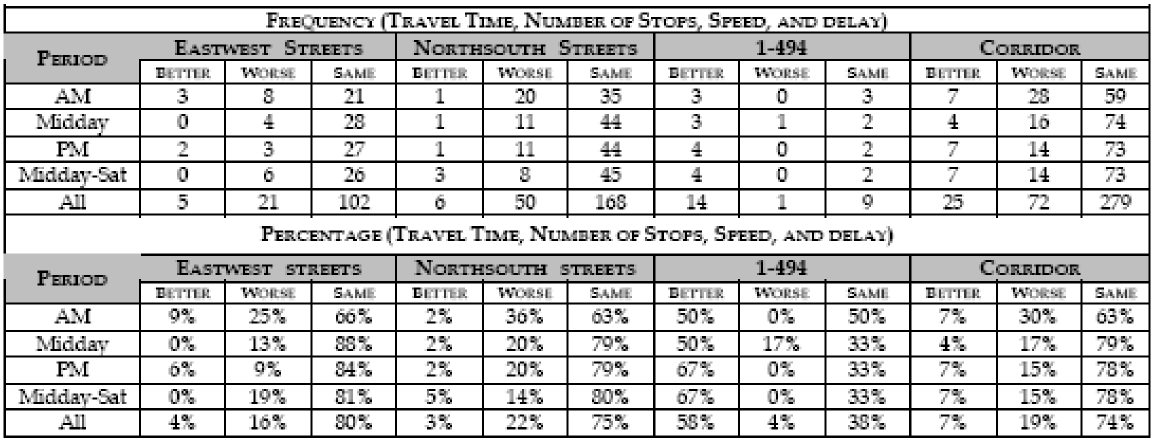
Most studies report absolute values, absolute differences, and percentage differences for each measure. Percent differences contribute the most to the uncertainty since percentages amplify differences in small numbers. For example, a change from 1 stop to 0.5 stops is a difference of 50 percent. If the after condition is worse, it could be reported as a 100 percent increase in stops from 0.5 to 1. Such a system might only be a mile in length. Another system with a reduction in stops from 14 to 7 along a 10-mile arterial would also be a 50 percent reduction in stops, but with substantially higher aggregated performance benefits. While percentages are easy for human brains to process (perhaps due to our consumerism culture of 50 percent off sales and the like), there is definitely a need to identify reporting methods that allow fairer comparisons of performance (see Figure 30).



NORTHBOUND										
Measure of Effectiveness (Average per Run)	AM			Midday			PM			Avg %Δ
	Existing System	InSync	%Δ	Existing System	InSync	%Δ	Existing System	InSync	%Δ	
Travel Time (sec)	86	76.8	**-11%**	115.9	70.3	**-39%**	111.9	62.7	**-44%**	**-31%**
# of Stops	0.9	0.6	**-33%**	1	1.1	**10%**	1.3	1	**-23%**	**-15%**
Total Delay (sec)	66.4	57.1	**-14%**	96.1	50.7	**-47%**	92.3	43.3	**-53%**	**-38%**
Avg Speed (mph)	9.9	11.1	**12%**	7.4	12.1	**64%**	7.6	13.6	**79%**	**52%**

Figure 17. Table. A Typical Evaluation Report Summary Table.
(Source: TJKM, 2011.)

Some evaluations have used other ways of aggregating performance (MnDOT, 1995; NCHRP 03-90, in press) such as accumulating the number or percentage of links that were “better,” “worse,” or “same” into bins by time of day and direction of travel. The MnDOT study on the ICTM (which included both freeway ramp metering and arterial ASCT) is notable in that they reported performance both before and after adjusting for volume changes as illustrated in Figure 18 and Figure 19. Notice in Figure 19 that after adjusting for flow rate differences, the number of links that are “better” increases substantially due to the 3 years of difference between when the “before” data was collected to when the system was fully installed and evaluated. More study is needed to determine the methodology used to adjust the results for volume differences.



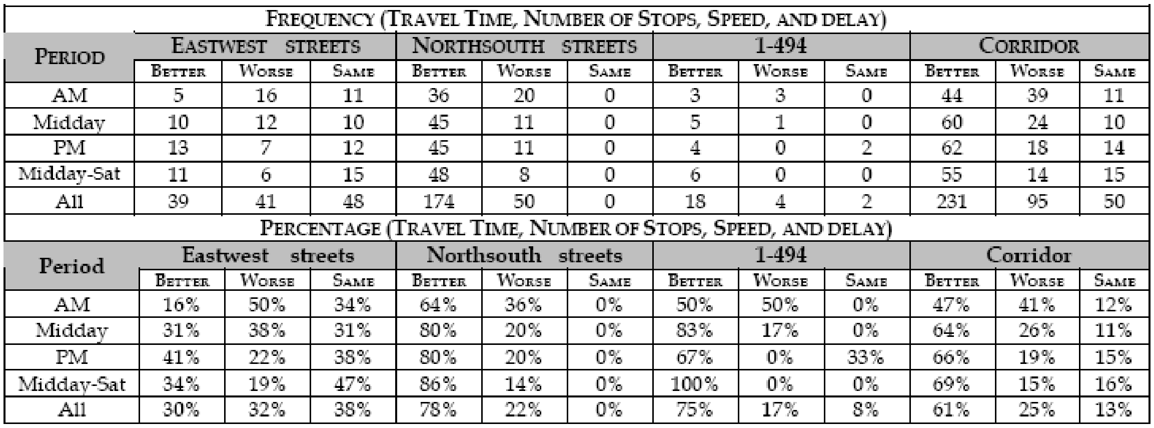
Frequency (Travel Time, Number of Stops, Speed, and delay)

Period	Eastwest Streets			Northsouth Streets			1-494			Corridor		
	Better	Worse	Same	Better	Worse	Same	Better	Worse	Same	Better	Worse	Same
AM	3	8	21	1	20	35	3	0	3	7	28	59
Midday	0	4	28	1	11	44	3	1	2	4	16	74
PM	2	3	27	1	11	44	4	0	2	7	14	73
Midday-Sat	0	6	26	3	8	45	4	0	2	7	14	73
All	5	21	102	6	50	168	14	1	9	25	72	279

Percentage (Travel Time, Number of Stops, Speed, and delay)

Period	Eastwest streets			Northsouth streets			1-494			Corridor		
	Better	Worse	Same	Better	Worse	Same	Better	Worse	Same	Better	Worse	Same
AM	9%	25%	66%	2%	36%	63%	50%	0%	50%	7%	30%	63%
Midday	0%	13%	88%	2%	20%	79%	50%	17%	33%	4%	17%	79%
PM	6%	9%	84%	2%	20%	79%	67%	0%	33%	7%	15%	78%
Midday-Sat	0%	19%	81%	5%	14%	80%	67%	0%	33%	7%	15%	78%
All	4%	16%	80%	3%	22%	75%	58%	4%	38%	7%	19%	74%

Figure 18. Table. Summary of Performance in “Better,” “Worse,” and “Same.”
(Source: MnDOT.)



Frequency (Travel Time, Number of Stops, Speed, and delay)

Period	Eastwest streets			Northsouth streets			1-494			Corridor		
	Better	Worse	Same	Better	Worse	Same	Better	Worse	Same	Better	Worse	Same
AM	5	16	11	36	20	0	3	3	0	44	39	11
Midday	10	12	10	45	11	0	5	1	0	60	24	10
PM	13	7	12	45	11	0	4	0	2	62	18	14
Midday-Sat	11	6	15	48	8	0	6	0	0	55	14	15
All	39	41	48	174	50	0	18	4	2	231	95	50

Percentage (Travel Time, Number of Stops, Speed, and delay)

Period	Eastwest streets			Northsouth streets			1-494			Corridor		
	Better	Worse	Same	Better	Worse	Same	Better	Worse	Same	Better	Worse	Same
AM	16%	50%	34%	64%	36%	0%	50%	50%	0%	47%	41%	12%
Midday	31%	38%	31%	80%	20%	0%	83%	17%	0%	64%	26%	11%
PM	41%	22%	38%	80%	20%	0%	67%	0%	33%	66%	19%	15%
Midday-Sat	34%	19%	47%	86%	14%	0%	100%	0%	0%	69%	15%	16%
All	30%	32%	38%	78%	22%	0%	75%	17%	8%	61%	25%	13%

Figure 19. Table. Summary of Performance Adjusted for Volume Changes.
(Source: MnDOT.)

Figure 20 illustrates another method for summary of network performance that might be applied to ASCT validation. Papamichail et al., (2009) used these graphs to illustrate how the distribution of performance across a network is improved in the before and after cases in Melbourne, Australia.

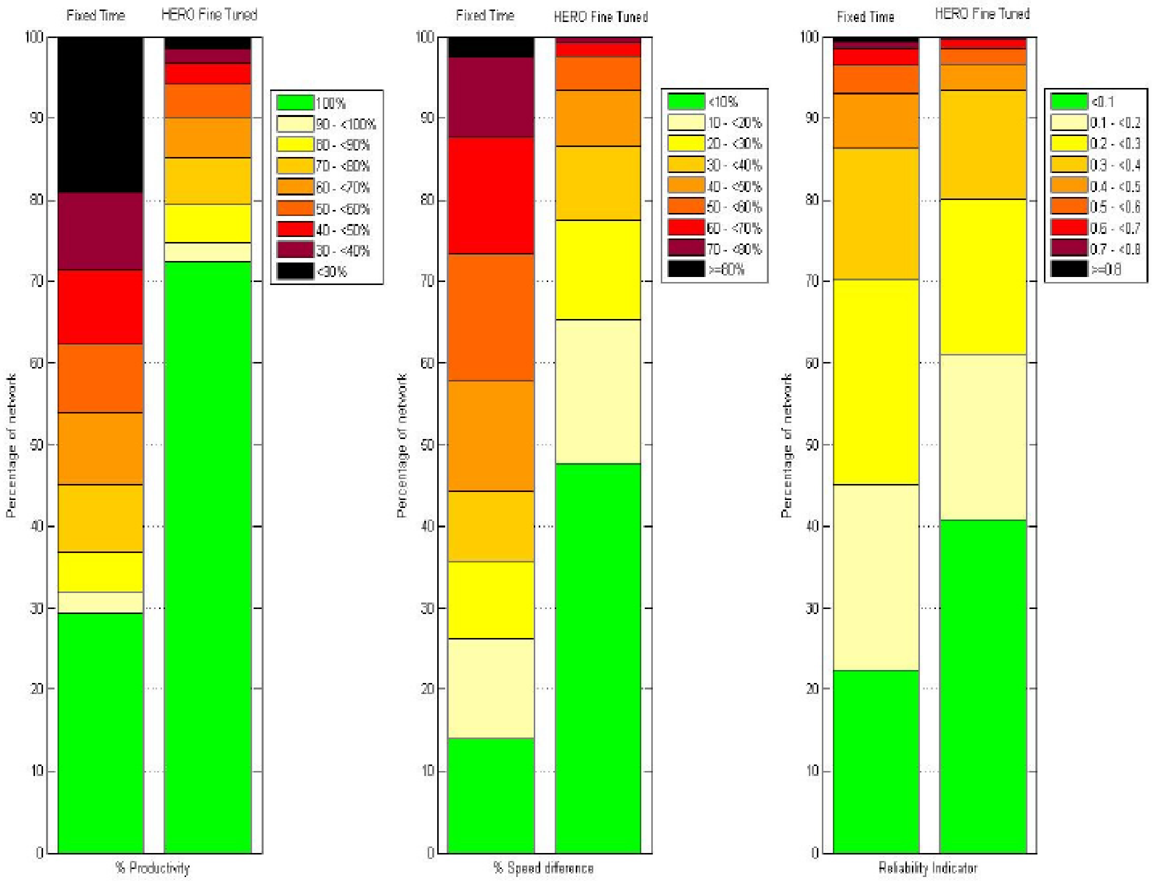


Figure 20. Diagram. Example of Aggregate Performance Indicators For Summary Performance of a Network.
(Source: Papamichail et al., 2009.)

Other studies (Pesti et al., 1999) have shown performance differences in a graphical format as illustrated in Figure 21. Such graphics are helpful in identifying performance benefits in a more user-friendly way than tabular summaries.

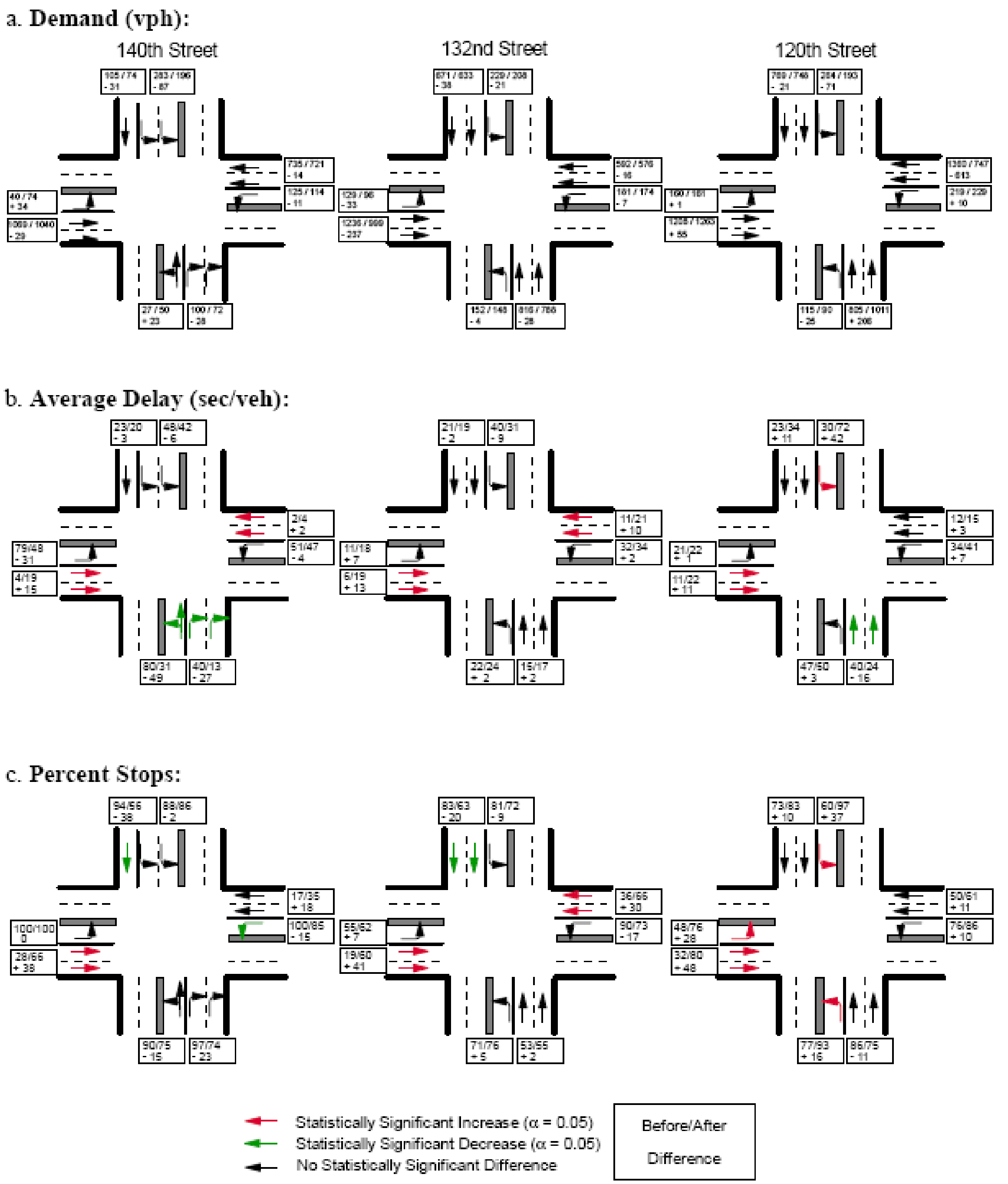
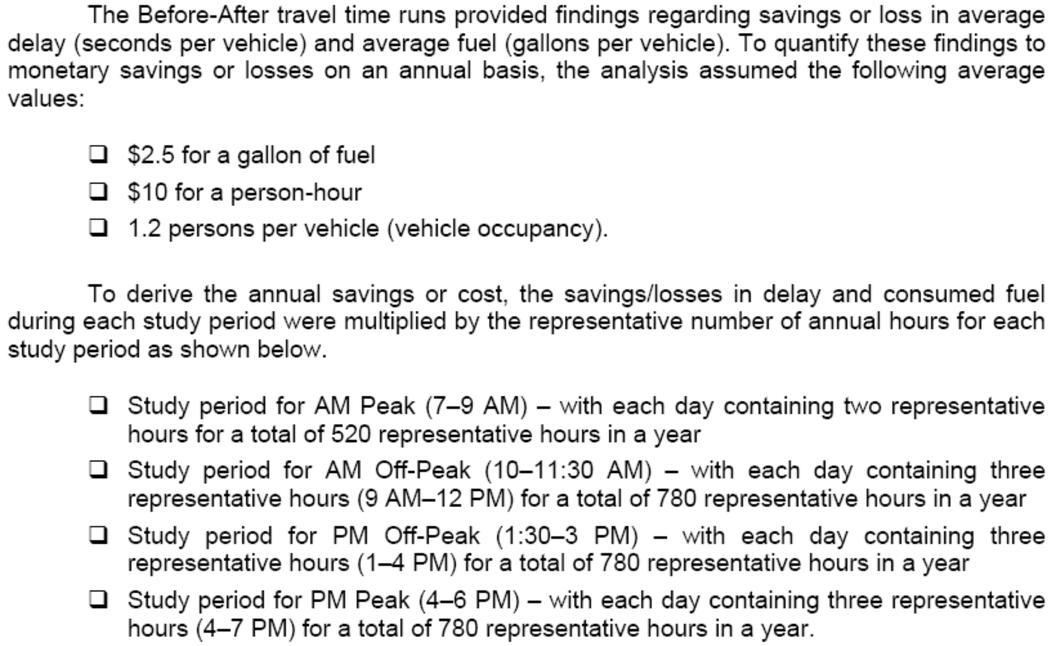


Figure 21. Exhibit. Graphical Example of Statistically Different Performance by Movement (Source: Pesti et al., 1999.)

EXTRAPOLATION TO BENEFIT/COST

Similarly, when average results in a limited study are used to extrapolate future performance in benefit/cost assessments, it is assumed that the percentage savings would simply accrue at the same rate for the system life cycle. Typical assumptions and resulting exhibit are illustrated in Figure 22 and Figure 23. Since most agencies retime signals either on a scheduled basis or based on trouble calls, some accommodation for these improvement activities needs to be taken into account in order to make the B/C estimates more from ASCT more realistic.



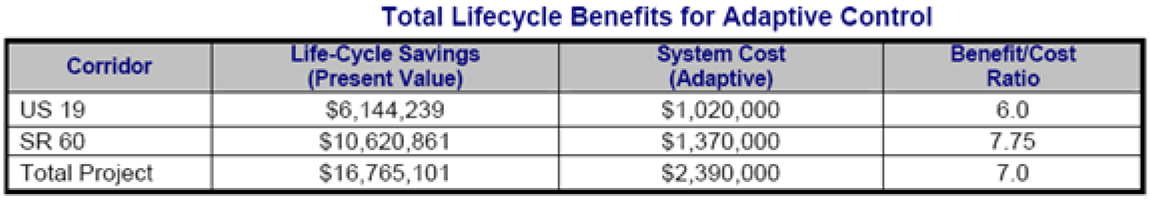
The Before-After travel time runs provided findings regarding savings or loss in average delay (seconds per vehicle) and average fuel (gallons per vehicle). To quantify these findings to monetary savings or losses on an annual basis, the analysis assumed the following average values:

- ☐ $2.5 for a gallon of fuel
- ☐ $10 for a person-hour
- ☐ 1.2 persons per vehicle (vehicle occupancy).

To derive the annual savings or cost, the savings/losses in delay and consumed fuel during each study period were multiplied by the representative number of annual hours for each study period as shown below.

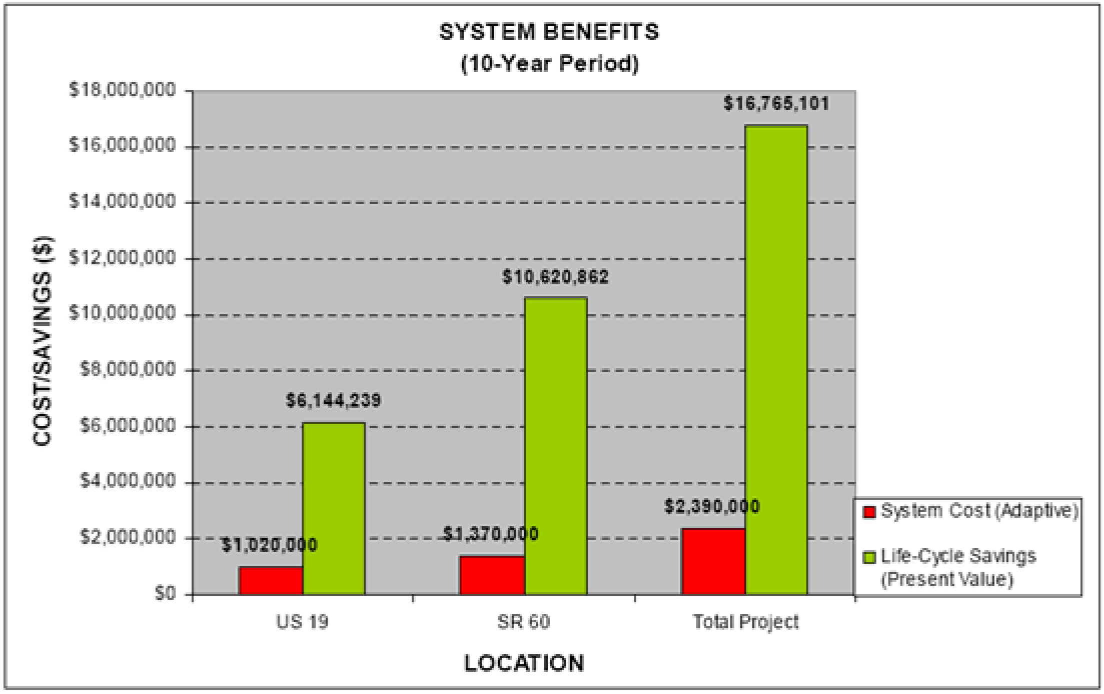
- ☐ Study period for AM Peak (7–9 AM) – with each day containing two representative hours for a total of 520 representative hours in a year
- ☐ Study period for AM Off-Peak (10–11:30 AM) – with each day containing three representative hours (9 AM–12 PM) for a total of 780 representative hours in a year
- ☐ Study period for PM Off-Peak (1:30–3 PM) – with each day containing three representative hours (1–4 PM) for a total of 780 representative hours in a year
- ☐ Study period for PM Peak (4–6 PM) – with each day containing three representative hours (4–7 PM) for a total of 780 representative hours in a year.

Figure 22. Exhibit. Example Assumptions for B/C Estimation.
(Source: Pinellas County, Florida, 2007.)



Total Lifecycle Benefits for Adaptive Control

Corridor	Life-Cycle Savings (Present Value)	System Cost (Adaptive)	Benefit/Cost Ratio
US 19	$6,144,239	$1,020,000	6.0
SR 60	$10,620,861	$1,370,000	7.75
Total Project	$16,765,101	$2,390,000	7.0



Adaptive system implementation benefits over 10 years

Figure 23. Exhibit. Example Benefit/Cost Exhibit.
(Source: Pinellas County, Florida, 2007.)

EXPLICIT STATEMENT OF GOALS

It has been uncommon for agencies to provide targets for improvement goals in system deployments. One study in Menlo Park, California did identify target performance goals for travel time, stops, side-street delay, and average speed (7 percent improvement to stops and 5 percent improvement for the other measures) and the evaluation showed that these goals were met for off-peak times. Lower goals were applied for p.m. peak periods and the ASCT largely met those goals as well (Menlo Park, 2003).

CHAPTER 9. ANNOTATED BIBLIOGRAPHY OF REPRESENTATIVE ASCT EVALUATION STUDIES

ALPHABETICAL LISTING BY PRIMARY AUTHOR OR AGENCY

CCS Planning and Engineering, *El Camino Real (Route 82) Adaptive Traffic Signal Coordination Project,* City of Menlo Park, California, Draft Final Report dated August 29, 2003.

> Study report focused on SCATS deployment in Menlo Park, California. Performance measures were stops, delay, and average speed.

Chatila, H., and Zehn, L., *U.S. 95 ACS-Lite System Evaluation*, Memorandum to Idaho Transportation Department, The Transpo Group, November 29, 2007.

> This study conducted simulation analysis of ACS-LITE using VISSIM. The primary performance criterion was arterial travel time.

Dowling, R., *Guide on the Consistent Application of Traffic Analysis Tools and Methods*. November 2011. Report number FHWA-HRT-11-064, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 2011.

Fehon, K., and Peters, J., *Adaptive Traffic Signals, Comparison and Case Studies*, Paper presented at the ITE Western District Annual Meeting in San Francisco, California, 2010.

> This paper compared and contrasted the systems that have been successfully installed in the USA and discussed their advantages and disadvantages. The discussion includes several case studies in which the authors investigated the options available to agencies, discusses the reasons why different systems were selected for installation, and presents the results of detailed evaluations of the effectiveness of each installed system. The paper also describes the evaluation techniques that were used to provide statistically reliable evaluation results, overcoming the shortcomings that are often found in traffic engineering surveys.

Fehon, K., *Adaptive Traffic Signals: Are We Missing The Boat?* Paper presented at the ITE District 6 Annual Meeting, 2004.

> This paper examines the reasons why the existing successful systems have failed to gain acceptance, why the newly developed systems have not yet been successfully demonstrated, and questions the validity of the reasons commonly put forward for this situation.

Gord, A., *Adaptive Versus Traditional Traffic Control Systems, A Field-Based Comparative Assessment,* Evaluation White Paper as part of the Pinellas Countywide ATMS Project, Gord & Associates, Inc., Financial Project ID: 408419-1-32-01, March 2007.

> This study evaluated OPAC on U.S. 19 and RHODES on SR 60. The performance measures were: safety, mobility, efficiency, energy, and productivity. Mobility was measured using

travel time, stops, speed and delay. Travel time, stops, speed and delay were collected with the use of GPS. Efficiency was measured as throughput. Energy was measured as fuel emissions, and productivity was measured as fuel and control delay. Extensive use of tables and charts.

Martin, P., Stevanovic, A, Vladisavljevic, I. *Adaptive Signal Control IV, Evaluation of the Adaptive Traffic Control System in Park City, Utah.* University Transportation Centers Program, 2006.

The goal of the project was to assess the effectiveness of the future UDOT ATCS relative to existing traffic control system, and to transfer ATCS expertise from the Vendor to UDOT staff. MOEs were stopped delay, corridor travel time, average speed, stops, cycle length, and traffic demand.

Data collection was stopped-time delay studies on 12 intersections. Turning movement counts were used to relate relevant stopped delay studies with concurrent traffic demand, and input in simulation. The CORSIM and VISSIM simulation models were connected to SCOOT.

Research objectives were to define the traffic efficiency criteria that Utah's first ATCS should meet, define MOE's to assess the criteria, conduct a before and after study, and "with" and "without" evaluations, and to assess operator's acceptance of ATCS technology. The "with" and "without" evaluation used field data measurement (intersection delay and travel time), and network simulation.

Nandam, K.L., and Hess, D., *Dynamic Change of Left Turn Phase Sequence between Time-of-Day Patterns – Operational and Safety Impacts*. Institute of Transportation Engineers 2000 Annual Conference, Nashville, Tennessee, August 2000.

This report used vehicle stops, delay, and travel time as the primary performance measure, but also looked at crash data. The result of the study was that changing signal phasing by time of day did not affect safety.

NCHRP – National Cooperative Highway Research Program. *Quantifying Congestion. Volume 1 – Final Report.* NCHRP 398. Transportation Research Board, Washington, D.C., 1997.

Pesti, G., Byrd, P.S., Kruse, M., and McCoy, P.T., *Demonstration of State-of-the-Art Integrated Traffic Management System: Evaluation of the SPOT Adaptive Traffic Control System*, University of Nebraska-Lincoln, Report No. 97068, May 1999.

This study evaluated the effectiveness of the PEEK SPOT adaptive system on an arterial street that experienced large, sudden, and unpredictable changes in traffic flow in Omaha, NE. Performance measures studied were: stopped-time delay and travel-time delay conducted in a "before and after" condition. The study showed that the SPOT system increased travel time, delay, and stops. The report contains several valuable examples of performance visualization approaches.

Peters, J., McCoy, J., Bertini, R., *Evaluating an Adaptive Signal Control System in Gresham*, ITE District 6 Annual Meeting, Portland, Oregon, July 2007.

> A limited study of the SCATS deployment in Gresham, Oregon which looked at travel time, stops, delay and fuel consumption. The goal of the deployment was to reduce travel time through the corridor and implement a user-friendly system. By all accounts the authors report a successful project; although there was limited field data reported. The report was premature in that data collection was underway at the time of reporting. No follow up study results could be located.

Robertson, H.D., J.E. Hummer, and D.C. Nelson. *Manual of Transportation Engineering Studies*. Institute of Transportation Engineers. Prentice-Hall, Englewood Cliffs, New Jersey. 1994.

> This manual provides the basis for conducting travel time delay studies.

Selinger, M., and Schmidt, L., *Adaptive Traffic Control Systems in the United States: Updated Summary and Comparison.* HDR, 2010.

> Survey findings indicate that the definition of Adaptive traffic control is: "an advanced traffic signal control system that updates traffic signal timing in some automated way." Operational objectives were to improve: arterial travel time, arterial delay, number of stops, intersection delay, queue lengths, and average speed.

Smaglik, E., Bullock, D., Gettman, D., Day, C., Premachandra, H., *Comparison of Alternative Real-Time Performance Measures for Measuring Signal Phase Utilization and Identifying Oversaturation.* TRB Paper 11-0931. Presented at the 89th Annual Meeting of the Transportation Research Board, Washington, D.C., 2011.

> This study analyzed the difference between calculated GOR and V/C ratios over different detection zone lengths and differing vehicle speeds, compares these values to a calculated delay metric, and observes the effectiveness of GOR as an indicator of oversaturation.

Smaglik, E., Bullock, D., and Sharma, A., *Pilot Study on Real-Time Calculation of Arrival Type for Assessment of Arterial Performance,* Published in the Journal of Transportation Engineering (July 2007), 133(7): 415-422.

> Good study that identified that a tool is needed to quantify progression quality. The preferred tool would use phase status and time-stamped vehicle arrivals to determine arrival types. Common traffic controllers currently bin data in sizes between 5- to 10-minute intervals, but there is no consistency. This is an easy metric to calculate but the authors identify that automated means to collect the data are needed.

Stevanovic, A., Kergaye, C., and Martin, P., *SCOOT and SCATS: A Closer Look into Their Operations.* Presented at the 88th Annual Meeting of the Transportation Research Board*,* Washington, D.C., 2009.

> This study compared SCOOT and SCATS signal timing using VISSIM. The study of the SCATS system used real-world data; whereas the SCOOT data was derived through the use of simulation. Study looked at cycle lengths, offsets, and splits and compared those factors to segment performance measures of total intersection delay, throughput, and quality of progression between adjacent intersections. The evaluation was limited to pairs of intersections.

Stevanovic, A., Stevanovic, J., Jolovic, D., Nallamothu, V., *Retiming Traffic Signals to Minimize Surrogate Safety Measures on Signalized Road Networks.* Presented at the 91st Annual Meeting of the Transportation Research Board, Washington, D.C., 2012.

> Study used VISSIM, SSAM, and VISGAOST for optimizing signal timing to reduce surrogate safety measures and thus reduce risk of potential real-world crashes.

Tarnoff, P. (2009a) *Blue Sky Thinking* in Thinking Highways, Vol. 4 No. 1, www.thinkinghighways.com.

Tarnoff, P. (2009b) *Made to Measure* in Traffic Technology International, April/May 2009.

Volling, M.T., *Arterial Travel Time Using Magnetic Signature Reidentification Theory of Application and ITS deployments in San Diego*, Presentation at ITS America, 2009.

Tindale-Oliver & Associates, Inc., *Martin County Advanced Traffic Management Systems (ATMS) Assessment.* Final Report prepared for Martin County, Florida, 2008.

> The purpose of this project was to estimate the benefits and costs associated with deploying an ATMS for the Martin County region. Study looked at deployment on five corridors. Existing condition was MarcNX closed-loop system. Report identified the benefits of the ACS-Lite installation in Bradenton, Florida, SCATS in Broward County and Pasco, Florida, SCOOT in Collier County, and RHODES and OPAC in Pinellas County, Florida. The study considered delay, stops and travel time performance measures. The study was focused on MOEs and cost of deployment.

TJKM Transportation Consultants, *Evaluation of Main Street Adaptive Traffic Signal Systems*, Technical Report prepared for the City of South San Francisco, May 11, 2011.

> Study of MOEs for InSync deployment.

Turner, S., Eisele, W., Benz, R., and Holdener, D., *Travel Time Data Collection Handbook*, Texas Transportation Institute Research Report 07470-1F, Federal Highway Administration, FHWA-PL-98-035, Washington, D.C., 1998.

FHWA and TTI study on data collection. Chapter 3 identifies test vehicles.

Wang, J., Robinson, B., Shelby, S., Cox, K., Townsend, W., *Evaluation of ACS Lite Adaptive Control using Sensys Arterial Travel Time Data*, Presented at ITS America 20th Annual Meeting and Exposition in Houston, Texas, 2010.

This paper describes the deployment of an ACS Lite adaptive control system on an arterial in Atlanta, Georgia, and presents a performance evaluation including arterial travel time measures obtained using a vehicle reidentification system. The results of this study showed that the deployed ACS Lite system substantially reduced arterial travel time and side-street queue lengths during peak traffic flow periods. The performance measures were travel time and queue lengths on side-streets. Queue length data collected manually using staff of 5 stationed at each intersection to record maximum number of vehicles in queue at onset of each green cycle. Arterial travel time data was collected by Sensys system.

Wetzel, C., and Dickson, C., *SynchroGreen Real-Time Adaptive Traffic Control System, Seminole County SR 436 Deployment*. White Paper by Seminole County Public Works/Traffic Engineering Division, Seminole County, Florida, 2011.

This paper evaluated SynchroGreen deployed in Seminole County, Florida. The study evaluated vehicle and pedestrian traffic. Traditional performance measures were considered, those being: travel time, delay, and stops. In addition, the study considered side-street delay and pedestrian delay. The authors used “on-off” technique to measure the effectiveness. Arterial travel time, delay and stop data was collected with the use of a GPS receiver. Side-street delay was collected based on the 2010 HCM procedures at two intersections over a 30-minute period in 15-second count intervals. Pedestrian delay was measured in the field with a stop watch at three intersections. Emission data was simulated using MICRO2, which was included in the GPS software.

APPENDIX A. TECHNICAL APPROACH FOR COLLECTING MOES

There are four types of data necessary for computing the MOEs presented in the previous sections:

- High-resolution phase timing and detector actuation data collected by the ASCT, signal system, or controller;
- GPS probe vehicle trajectory data;
- Travel time and origin-destination data collected by vehicle re-identification equipment; and
- Volume data collected by system detection zones or vehicle counting equipment.

To validate objectives of ASCT, the first step is to collect any or all of these data elements. From these four basic sources, the next step is to ingest and store the data in a common database and process the data further. MOEs are then computed as requested by an analyst. This generic process is illustrated in Figure 24. Data formats and technologies for each of the types of data are discussed in the following sections.

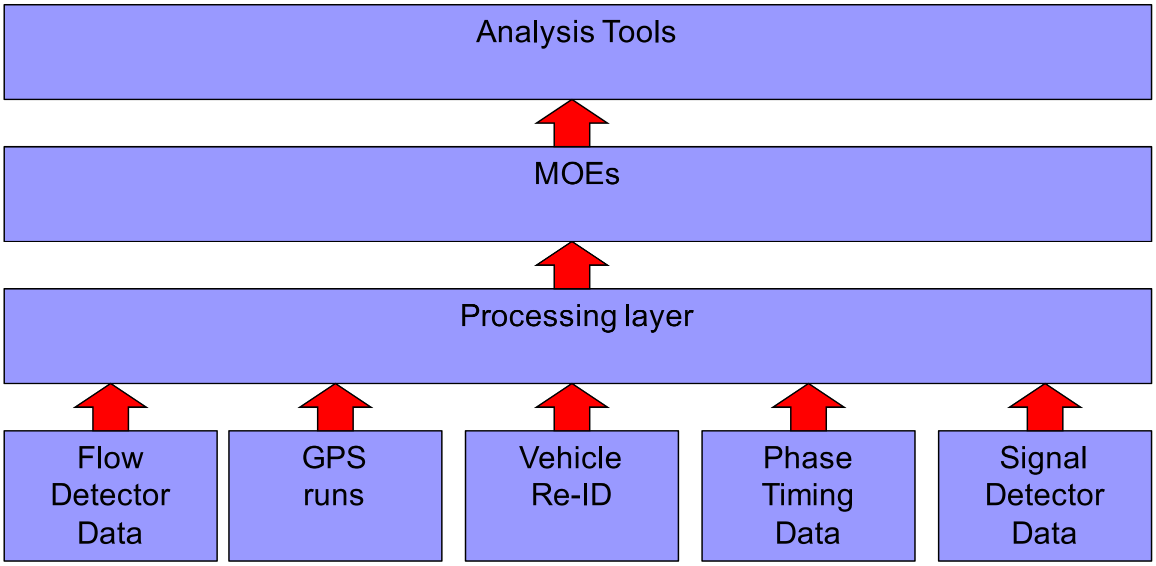


Figure 24. Diagram. Generic Illustration of the Data Collection and Processing Methodology. (Source: Kimley-Horn and Associates, Inc.)

HIGH-RESOLUTION PHASE TIMING AND DETECTOR DATA

High-resolution phase and detector data can be recorded in one of two ways, either as time-stamped events or as raw status entries for every time slice. Modern controllers typically run the clock at 0.1s increments, but in most cases 1s increments should be suitable for performance measurement purposes. Some storage methods record detector data in subsecond increments each second to capture the case where a detector is active only a subset of the 0.1s increments of that second. Several controllers are known to store this information on the controller and allow an external process to retrieve the information as a binary file via FTP. Other controller vendors may be in the process of adding similar logging functionality. In the case of the one controller type, the storage is one file per hour of the day, so only one query per hour from an external process is necessary. A software application provided by the vendor is needed to convert the binary data to a generic CSV format. This makes the data accessible in near real-time while minimizing bandwidth requirements and the reliance on continual connectivity.

Some ASCT are known to store event-based phase timing and detector data on a daily basis. For example, one ASCT system stores second-by-second phase timing and detector data for each intersection in one .ZIP[6] file for each intersection for each day. An external process can retrieve this raw data from a field or central ASCT server on a daily basis (e.g., 3:00 a.m.) using common file transfer tools. This approach does not provide the data close to real-time, but does not require a connection to every field controller. The ZIP files are typically larger than the hourly files stored by a controller. Other performance measurement systems such as the cabinet harness equipment developed by TTI or University of Minnesota store event based data in an SQL database on the field-hardened PC processor in the cabinet.

Some central systems poll controllers every second for phase timing and detector status data and archive this information in binary files or SQL database tables for analysis or display. This storage methodology provides the information in as close to real-time as possible, but is contingent upon constant reliable communication to each controller (see Figure 25).

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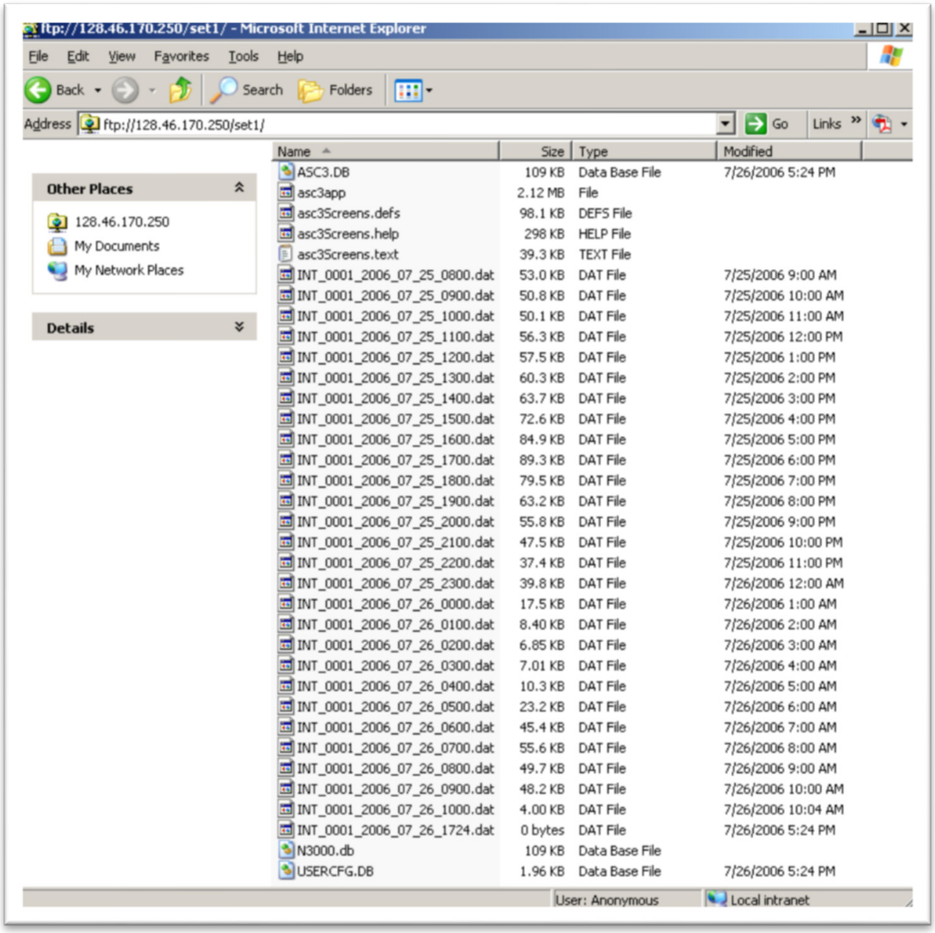
[6] A .ZIP file is a popular data compression format.



Name	Size	Type	Modified
ASC3.DB	109 KB	Data Base File	7/26/2006 5:24 PM
asc3app	2.12 MB	File	
asc3Screens.defs	98.1 KB	DEFS File	
asc3Screens.help	298 KB	HELP File	
asc3Screens.text	39.3 KB	TEXT File	
INT_0001_2006_07_25_0800.dat	53.0 KB	DAT File	7/25/2006 9:00 AM
INT_0001_2006_07_25_0900.dat	50.8 KB	DAT File	7/25/2006 10:00 AM
INT_0001_2006_07_25_1000.dat	50.1 KB	DAT File	7/25/2006 11:00 AM
INT_0001_2006_07_25_1100.dat	56.3 KB	DAT File	7/25/2006 12:00 PM
INT_0001_2006_07_25_1200.dat	57.5 KB	DAT File	7/25/2006 1:00 PM
INT_0001_2006_07_25_1300.dat	60.3 KB	DAT File	7/25/2006 2:00 PM
INT_0001_2006_07_25_1400.dat	63.7 KB	DAT File	7/25/2006 3:00 PM
INT_0001_2006_07_25_1500.dat	72.6 KB	DAT File	7/25/2006 4:00 PM
INT_0001_2006_07_25_1600.dat	84.9 KB	DAT File	7/25/2006 5:00 PM
INT_0001_2006_07_25_1700.dat	89.3 KB	DAT File	7/25/2006 6:00 PM
INT_0001_2006_07_25_1800.dat	79.5 KB	DAT File	7/25/2006 7:00 PM
INT_0001_2006_07_25_1900.dat	63.2 KB	DAT File	7/25/2006 8:00 PM
INT_0001_2006_07_25_2000.dat	55.8 KB	DAT File	7/25/2006 9:00 PM
INT_0001_2006_07_25_2100.dat	47.5 KB	DAT File	7/25/2006 10:00 PM
INT_0001_2006_07_25_2200.dat	37.4 KB	DAT File	7/25/2006 11:00 PM
INT_0001_2006_07_25_2300.dat	39.8 KB	DAT File	7/26/2006 12:00 AM
INT_0001_2006_07_26_0000.dat	17.5 KB	DAT File	7/26/2006 1:00 AM
INT_0001_2006_07_26_0100.dat	8.40 KB	DAT File	7/26/2006 2:00 AM
INT_0001_2006_07_26_0200.dat	6.85 KB	DAT File	7/26/2006 3:00 AM
INT_0001_2006_07_26_0300.dat	7.01 KB	DAT File	7/26/2006 4:00 AM
INT_0001_2006_07_26_0400.dat	10.3 KB	DAT File	7/26/2006 5:00 AM
INT_0001_2006_07_26_0500.dat	23.2 KB	DAT File	7/26/2006 6:00 AM
INT_0001_2006_07_26_0600.dat	45.4 KB	DAT File	7/26/2006 7:00 AM
INT_0001_2006_07_26_0700.dat	55.6 KB	DAT File	7/26/2006 8:00 AM
INT_0001_2006_07_26_0800.dat	49.7 KB	DAT File	7/26/2006 9:00 AM
INT_0001_2006_07_26_0900.dat	48.2 KB	DAT File	7/26/2006 10:00 AM
INT_0001_2006_07_26_1000.dat	4.00 KB	DAT File	7/26/2006 10:04 AM
INT_0001_2006_07_26_1724.dat	0 bytes	DAT File	7/26/2006 5:24 PM
N3000.db	109 KB	Data Base File	
USERCFG.DB	1.96 KB	Data Base File	7/26/2006 5:24 PM

Figure 25. Screen Shot. Hourly Phase and Detector Data Files from a Controller.
(Source: Smaglik et al., 2006.)

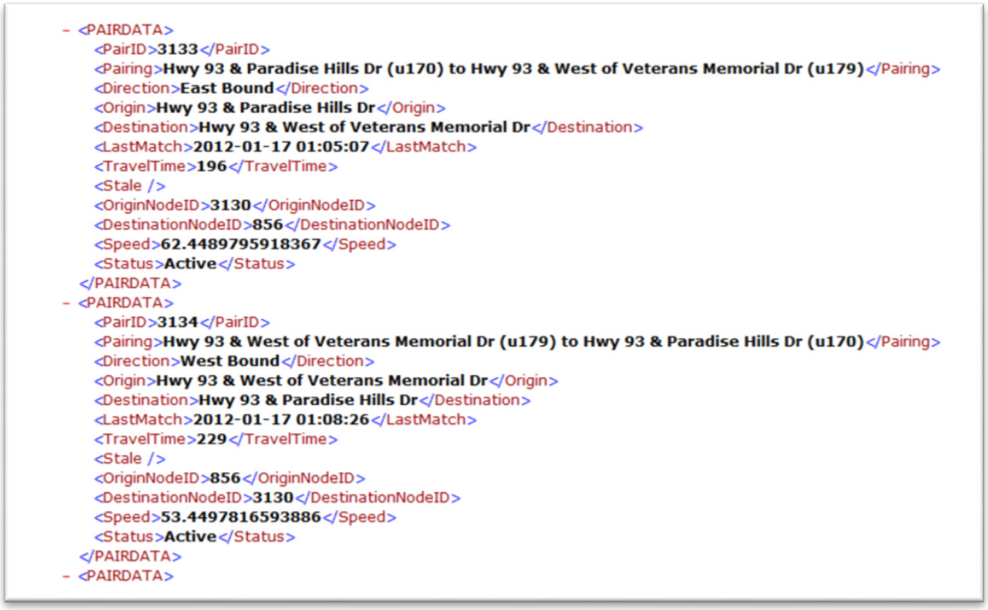
Each of these retrieval and storage methods use different formats and retrieval mechanisms. No industry-standard storage format or retrieval methodology has been established. For this project, all of these data availability methods cannot be implemented under the budget and schedule. Retrieval of high-resolution phase timing and detector data from the ASC/3 controller was implemented in this project. Once this high-resolution data is stored in a common database with the other data sources, the MOEs are computed.

VEHICLE RE-IDENTIFICATION DATA

There are several technologies that are available for measuring origin destination flows. These methods include:

- Bluetooth scanners.
- License plate readers.
- Magnetometers/inductive loop amplifiers.

All technologies have been shown to provide acceptable performance for measuring point to point travel times. No industry standard format exists for storage and reporting of the travel time information from the different field equipment types. Recently, several Bluetooth scanner vendors have promoted the use of the XML encoding format for providing feeds or file-based storage of travel time performance measurements. An example XML feed from a scanner server is shown in Figure 26.



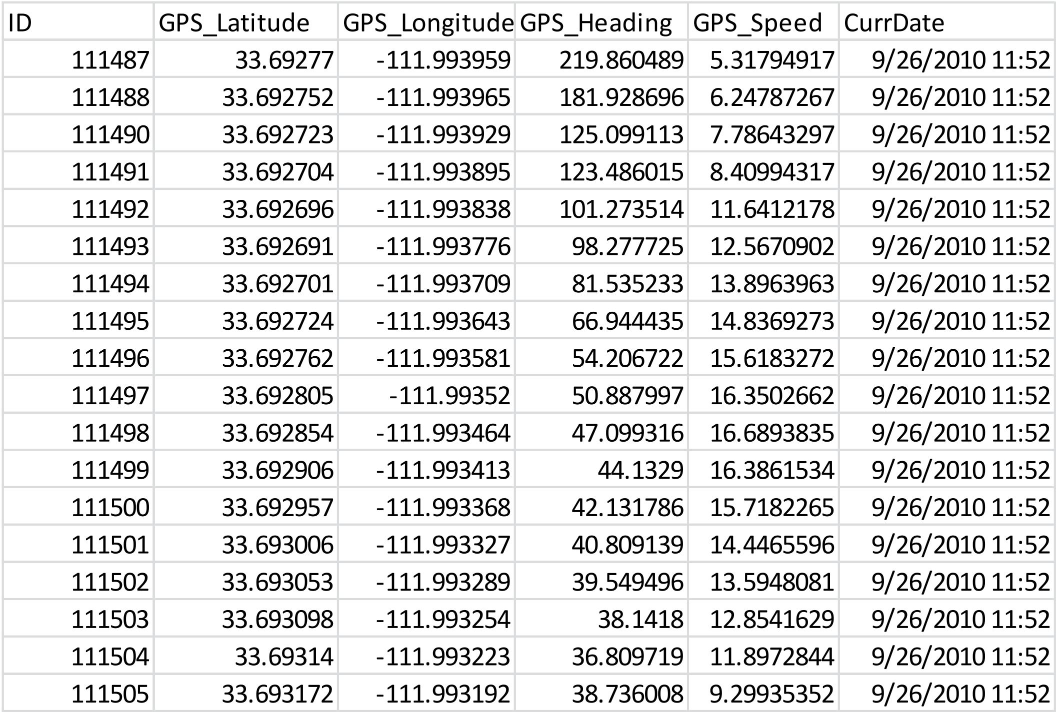
```
- <PAIRDATA>
    <PairID>3133</PairID>
    <Pairing>Hwy 93 & Paradise Hills Dr (u170) to Hwy 93 & West of Veterans Memorial Dr (u179)</Pairing>
    <Direction>East Bound</Direction>
    <Origin>Hwy 93 & Paradise Hills Dr</Origin>
    <Destination>Hwy 93 & West of Veterans Memorial Dr</Destination>
    <LastMatch>2012-01-17 01:05:07</LastMatch>
    <TravelTime>196</TravelTime>
    <Stale />
    <OriginNodeID>3130</OriginNodeID>
    <DestinationNodeID>856</DestinationNodeID>
    <Speed>62.4489795918367</Speed>
    <Status>Active</Status>
  </PAIRDATA>
- <PAIRDATA>
    <PairID>3134</PairID>
    <Pairing>Hwy 93 & West of Veterans Memorial Dr (u179) to Hwy 93 & Paradise Hills Dr (u170)</Pairing>
    <Direction>West Bound</Direction>
    <Origin>Hwy 93 & West of Veterans Memorial Dr</Origin>
    <Destination>Hwy 93 & Paradise Hills Dr</Destination>
    <LastMatch>2012-01-17 01:08:26</LastMatch>
    <TravelTime>229</TravelTime>
    <Stale />
    <OriginNodeID>856</OriginNodeID>
    <DestinationNodeID>3130</DestinationNodeID>
    <Speed>53.4497816593886</Speed>
    <Status>Active</Status>
  </PAIRDATA>
- <PAIRDATA>
```

Figure 26. Message. Example XML Feed from BT Scanner Server
(Source: Nevada DOT Freeway Management System, 2012.)

Bluetooth data from the BlueTOAD website using real-time XML retrieval was implemented in this project.

GPS PROBE DATA

GPS probe data is available from a variety of laptop and Smartphone applications and systems. There is no industry standard format for the storage of GPS probe data. Laptop applications typically provide probe data trajectories in CSV output files. Smartphone GPS applications typically store travel time run information on the phone as CSV files or alternatively they push location, velocity, etc., data to a web server in real-time for analysis and display as the driver progresses along the route. For this project, GPS probe data will be stored on a web site in a SQL table format that records the location, speed, heading, altitude, and acceleration of each probe trip. Figure 27 illustrates typical data format from GPS tracking devices.



ID	GPS_Latitude	GPS_Longitude	GPS_Heading	GPS_Speed	CurrDate
111487	33.69277	-111.993959	219.860489	5.31794917	9/26/2010 11:52
111488	33.692752	-111.993965	181.928696	6.24787267	9/26/2010 11:52
111490	33.692723	-111.993929	125.099113	7.78643297	9/26/2010 11:52
111491	33.692704	-111.993895	123.486015	8.40994317	9/26/2010 11:52
111492	33.692696	-111.993838	101.273514	11.6412178	9/26/2010 11:52
111493	33.692691	-111.993776	98.277725	12.5670902	9/26/2010 11:52
111494	33.692701	-111.993709	81.535233	13.8963963	9/26/2010 11:52
111495	33.692724	-111.993643	66.944435	14.8369273	9/26/2010 11:52
111496	33.692762	-111.993581	54.206722	15.6183272	9/26/2010 11:52
111497	33.692805	-111.99352	50.887997	16.3502662	9/26/2010 11:52
111498	33.692854	-111.993464	47.099316	16.6893835	9/26/2010 11:52
111499	33.692906	-111.993413	44.1329	16.3861534	9/26/2010 11:52
111500	33.692957	-111.993368	42.131786	15.7182265	9/26/2010 11:52
111501	33.693006	-111.993327	40.809139	14.4465596	9/26/2010 11:52
111502	33.693053	-111.993289	39.549496	13.5948081	9/26/2010 11:52
111503	33.693098	-111.993254	38.1418	12.8541629	9/26/2010 11:52
111504	33.69314	-111.993223	36.809719	11.8972844	9/26/2010 11:52
111505	33.693172	-111.993192	38.736008	9.29935352	9/26/2010 11:52

Figure 27. Table. Sample GPS Tracking Data.
(Source: Kimley-Horn Mobile Tracking System, 2010.)

GPS data from an Android smartphone app was supported in this project. Import of trajectories from other recording programs can be added at a later time.

MIDBLOCK DETECTION DATA

Volume data is available from a variety of types of field equipment, including:

- Tube counters.
- Stand-alone detection stations (radar, magnetometer, video).
- System detectors connected to traffic controllers (variety of technologies).

Tube counter equipment includes a relatively simple field processor unit that stores the count and classification data locally. Most counters allow data to be retrieved from the device via a USB or serial interface after the tube is removed from the field. Most if not all tube counter devices do not have remote communications capability. Count summaries are typically provided in configurable bins such as five-minutes, 15-minutes, etc. Data is typically aggregated for subsequent use in simple CSV format or formatted Excel spreadsheets.

Stand-alone detection stations typically aggregate volume and associated information at a central server in a SQL database. The industry-standard X3 protocol has been developed for retrieval of data from detection stations in real-time (primarily in freeway applications, but arterial deployments can use the same equipment and protocols). Typically detection stations are polled every 20 to 30s for a summary count over that time period instead of being interrogated every second like most traffic controllers. Other interfaces such as XML-RPC have also been used to retrieve information from detector stations for archiving and analysis or use in traffic-responsive algorithms.

System detectors are also frequently deployed and connected to traffic controllers. The traffic controller aggregates the count and occupancy data on a specified interval and allows a central system to poll the aggregated data. This polling is typically done no faster than once per minute, and it is more typical (although this is not recommended) to aggregate the information in longer intervals (five to 15 minutes). NTCIP and AB3418E define standard storage formats for the aggregated data. Other vendor-specific storage formats are also used for storing and retrieval of volume count and classification data.

All methodologies have been shown to provide acceptable performance for measuring screen-line counts and vehicle classification, with appropriate configuration and deployment. Due to budget and schedule constraints this project only used volume data from manual import of tube counter files. Other methods can be supported at a later time.

Table 8 maps each data source to the group of MOEs that need the data for computation.

Table 8. Mapping of MOEs to Data sources.

MOEs	Data Sources	Operational Objectives
• Route travel time • Route travel delay • Route average speed • Route travel time reliability	• Import travel time data from Bluetooth scanner • Import trajectory data from GPS probe	• Smooth flow • Multiple objectives by TOD
• Link travel time, delay • Number of stops per mile on route	• Import trajectory data from GPS probe	• Smooth flow • Manage queues • Multiple objectives by TOD
• Traffic volume on route (throughput) • Time to process equivalent volume	• Import count data from tube counter file	• Smooth flow • Manage queues • Multiple objectives by TOD
• Percent arrivals on green, by link • V/C ratio by movement • Platoon ratio, by link • Phase green to occupancy ratio by movement • Reliability of phase metrics	• Import high-resolution signal timing and detector data	• Smooth flow • Access equity • Multiple objectives by TOD

APPENDIX B. TOOL DESIGN AND DEVELOPMENT

The validation methodology requires collection and processing of the four basic sources of data discussed in the previous section. This information is then processed into MOEs. This requires development and implementation of software for this purpose. This software system is available via open source distribution at http://sourceforge.net/projects/fhwaasctvalidat/.
Figure 28 illustrates the focus of the project (highlighted in red) on the processing and computation of MOEs and provision of basic analysis tools. Except for GPS probe data, the project did not develop new data sources or formats for information from the field. In addition, the project did not focus on development of "dashboard" type visualization components or automated validation processes.

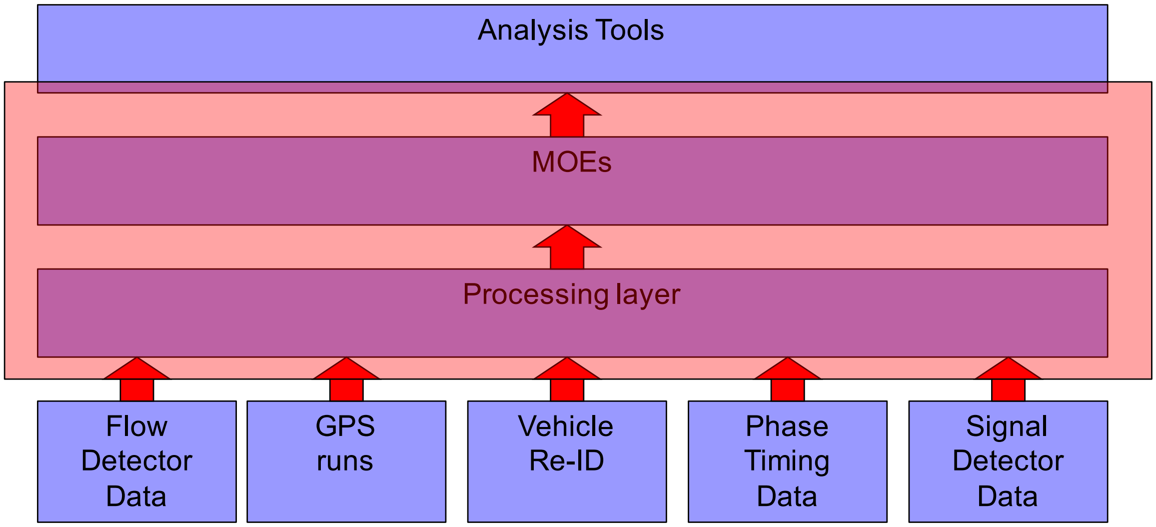


Figure 28. Diagram. Focus of the Tools Development Process.
(Source: Kimley-Horn and Associates, Inc.)

The processing layer allows the user to ingest the data sources into the website database. The MOEs are then calculated from the tabulated inputs. The analysis tools then allow the user to sort through the resulting measures and apply filters to some data elements to facilitate comparisons between "before" and the "after" conditions, or "ON" and "OFF" states, or to compare the performance of a strategy by time of day or day of week. The analysis tools do not require before and after conditions to be specifically identified if the user desires only to validate performance of one type of operation.

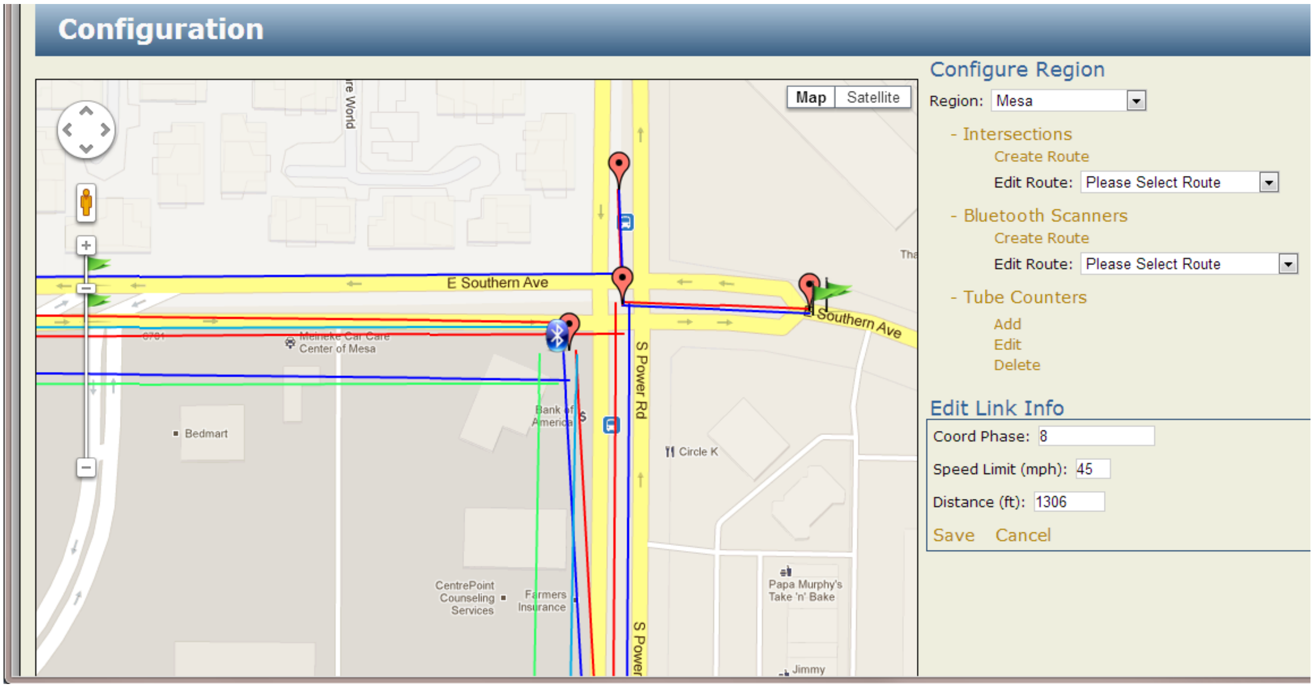
PROCESSING COMPONENTS

The first components that are needed are the methods to import the data from each data source and store the data in the database.

Configuration Data

A configuration page on the web site allows an administrator to add intersections, vehicle re-identification readers, traffic counters, and routes. Each route is composed of intersections and links added to the map in sequence. The Google distance Application Programming Interface (API) is used to calculate distances between markers, so curvature in the road is taken into account even though links between each point are shown as straight lines. Link distance is auto-calculated. The coordinated phase for a link is configured in order to correlate phase timing data from detectors to compute percent arrivals on green. The free-flow speed or speed limit (see Figure 29) is configured to compute link and route travel delays.

An important element of route configuration is to place a start point before the first intersection and a stop point after the last intersection at a reasonable distance from the intersection. Runs should be started before the start point and stopped after the stopping point in order to capture the effects of queues before entry to the first intersection. Runs should be randomized by drivers to enter equally when the light is red or green at the first location.



Region: Mesa

Edit Route: Please Select Route

Edit Route: Please Select Route

Coord Phase: 8

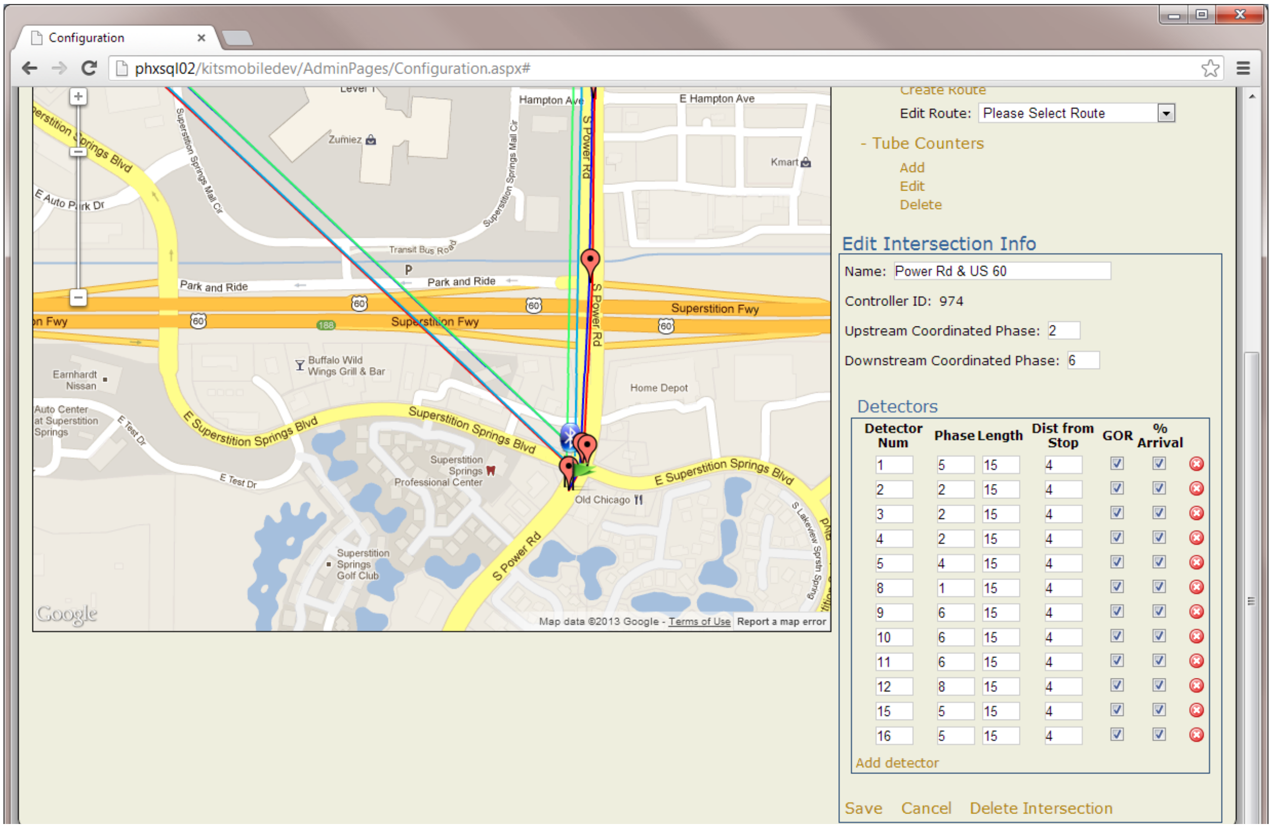
Speed Limit (mph): 45

Distance (ft): 1306

Figure 29. Screen Shot. Link Configuration Interface.
(Source: Kimley-Horn and Associates, Inc.)

Bluetooth detectors are added to the map and routes between one reader and another are defined by connecting the two. Traffic counters are added to the map and the direction of travel that they are counting is configured.

Detectors are added to intersections in order to calculate the Green-Occupancy Ratio (GOR) and percent arrivals on green by configuring their phase assignment, length, and distance upstream of the stop bar. This is illustrated in Figure 30. Refer to the previous report for details on the computation of GOR and percent arrivals on green.



Edit Route: Please Select Route

Edit Intersection Info

Name: Power Rd & US 60

Controller ID: 974

Upstream Coordinated Phase: 2

Downstream Coordinated Phase: 6

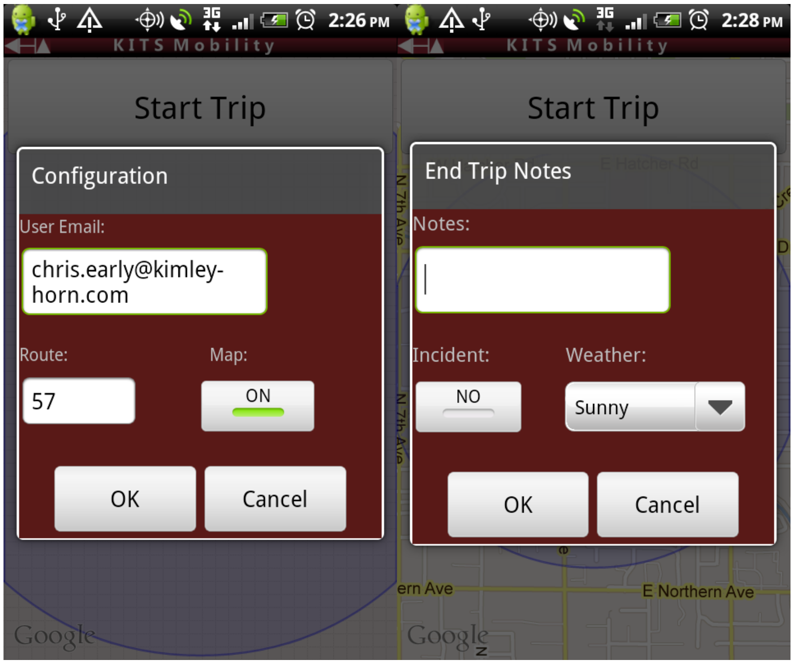
Detectors

Detector Num	Phase	Length	Dist from Stop	GOR	% Arrival	
1	5	15	4	☑	☑	✖
2	2	15	4	☑	☑	✖
3	2	15	4	☑	☑	✖
4	2	15	4	☑	☑	✖
5	4	15	4	☑	☑	✖
8	1	15	4	☑	☑	✖
9	6	15	4	☑	☑	✖
10	6	15	4	☑	☑	✖
11	6	15	4	☑	☑	✖
12	8	15	4	☑	☑	✖
15	5	15	4	☑	☑	✖
16	5	15	4	☑	☑	✖

Figure 30. Screen Shot. Detector Configuration Interface.
(Source: Kimley-Horn and Associates, Inc.)

GPS Probe Data

GPS probe data are ingested from an android smartphone application. The user of the application enters a user name and a route number. Pressing a “start trip” button begins the data collection. The application can safely be used by a single driver using a phone cradle, which creates no more driver distraction than entering basic information into a typical route guidance device. GPS coordinates, speed, and heading are recorded on the device, and there is no driver interaction with the device during the trip. The user then presses a “stop trip” button at the end of the route, which discontinues the data collection and feeds the trip data to the web site automatically using FTP. The user can optionally enter the weather conditions and determine if there was an incident that occurred or was passed during the drive. User notes are stored with each trip to identify any other anomalies or anecdotal experiences during the trip. These interfaces are illustrated in Figure 31.



User Email: chris.early@kimley-horn.com

Route: 57

Map: ON

Incident: NO

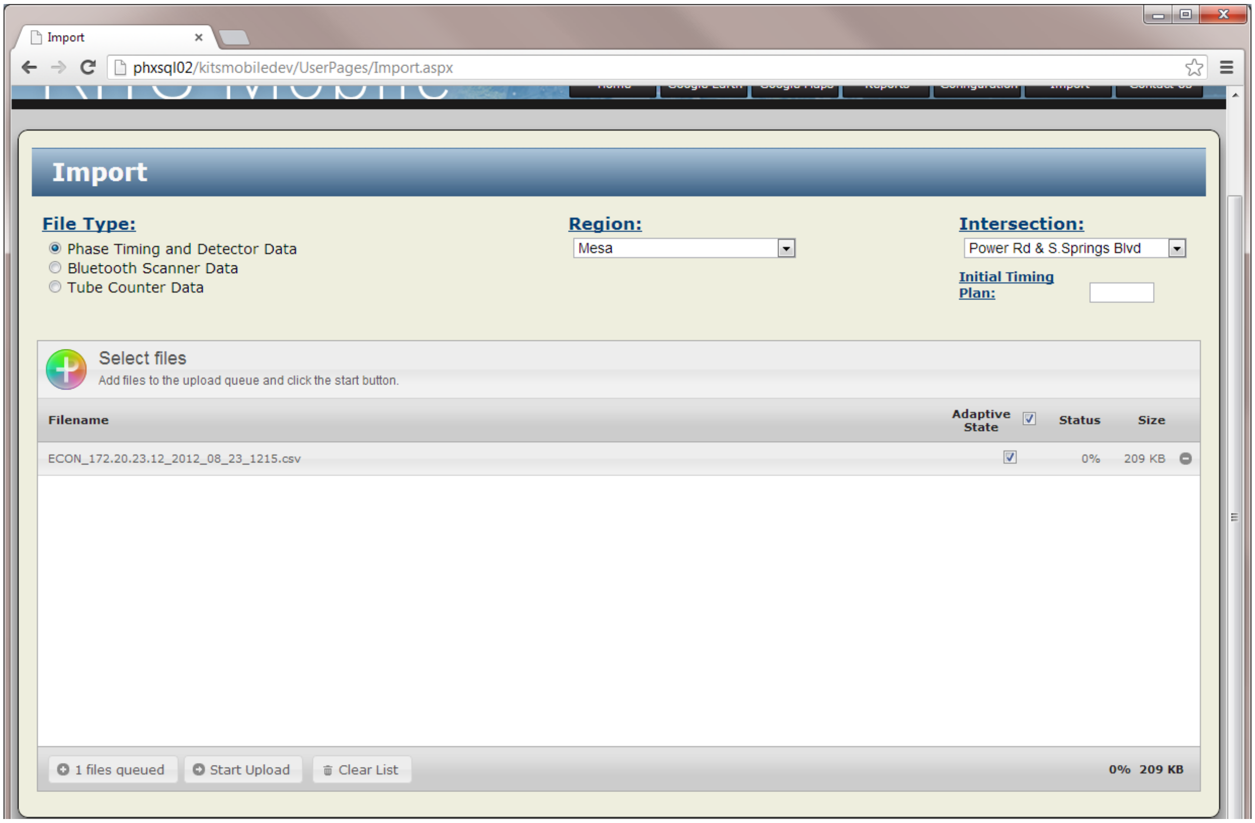
Weather: Sunny

Figure 31. Screen Shot. Android Smartphone Application Screens.
(Source: Kimley-Horn and Associates, Inc.)

GPS trips are allocated to “before” or “after” time periods manually through database scripts or editing in order to provide flexibility.

High-Resolution Phase Timing and Detector Data

High-resolution signal timing and detector data are read from files that are stored by a traffic controller on a daily basis. Binary log files are stored on the controller and uploaded by a software script using FTP. The binary files are converted to CSV files by a converter tool (provided to the project by Indiana DOT). For the ASC/3 controller, each file stores 15 minutes of data with each detector on and off event and phase interval change events encoded in the file. The directory fills quickly on the controller and the controller overwrites the files the next day with new information for that 15 minute period, so the data are uploaded on a daily basis. Those files are stored in a shared directory and then imported to the validation system via a manual import process using the web page illustrated in Figure 32.



Import

File Type:

- ● Phase Timing and Detector Data
- ○ Bluetooth Scanner Data
- ○ Tube Counter Data

Region: Mesa

Intersection: Power Rd & S.Springs Blvd

Initial Timing Plan:

Select files

Add files to the upload queue and click the start button.

Filename	Adaptive State ☑	Status	Size
ECON_172.20.23.12_2012_08_23_1215.csv	☑	0%	209 KB

Figure 32. Screen Shot. Import Interface.
(Source: Kimley-Horn and Associates, Inc.)

At the time of import, the analyst is responsible for determining whether the data are from ASCT operation by checking the box for each file. When the upload begins, the analysis process computes the MOEs and stores the information cycle-by-cycle in the database.

Bluetooth Scanner Data

Bluetooth route travel time data will be read from files that are stored by a Bluetooth scanner server on a daily basis. These files will store route travel time on a frequent basis (e.g., 15 minutes) and the number of matches in that time period for each configured node pair. In order to keep the system simple, the import interface will be manually driven. The user will select the files they want to import and add them to a selection dialog. The user can import a single file for a single day or multiple files for multiple days. They will mark each file as belonging to the "ON" or "OFF" time period. ON and OFF periods will not be allowable in periods shorter than a 24-hour period.

Similar to the setup for routes and intersections, Bluetooth scanner nodes will be configured on a Google map interface. A node will be given a name and an ID number. Routes will be created between nodes by associating one node with another. The distance of the route will be calculated using the Google API. A different kind of pin icon will be used for Bluetooth scanner nodes to distinguish the node from intersections or tube counters.

Tube Counter Data

Tube counter data will be read from files that are stored by a tube counter and exported using a USB memory stick. These files will store counts on a frequent basis (e.g., five minutes) for each direction of travel at the tube counter placement location. In order to keep the system simple, the import interface will be manually driven. The user will select the files they want to import and add them to a selection dialog. The user can import a single file for a single day or multiple days of data in a single file. The analyst will mark each file as belonging to the “ON” or “OFF” time period. ON and OFF periods will not be allowable in periods shorter than a 24-hour period.

Similar to the setup for routes and intersections, tube counter locations will be configured on a Google map interface. A tube counter will be given a name and an ID number that matches the ID number of the device in the field. Directional mnemonics will be marked for each counter location (e.g., eastbound, westbound) in order to appropriately allocate the field data when the information is imported. A different kind of pin icon will be used for tube counter nodes to distinguish the node from intersections or Bluetooth scanners.

MOE CALCULATIONS

After the data is imported, MOE calculations are made. Functional requirements for processing each source data type are described in the following sections.

Probe Travel Time Data

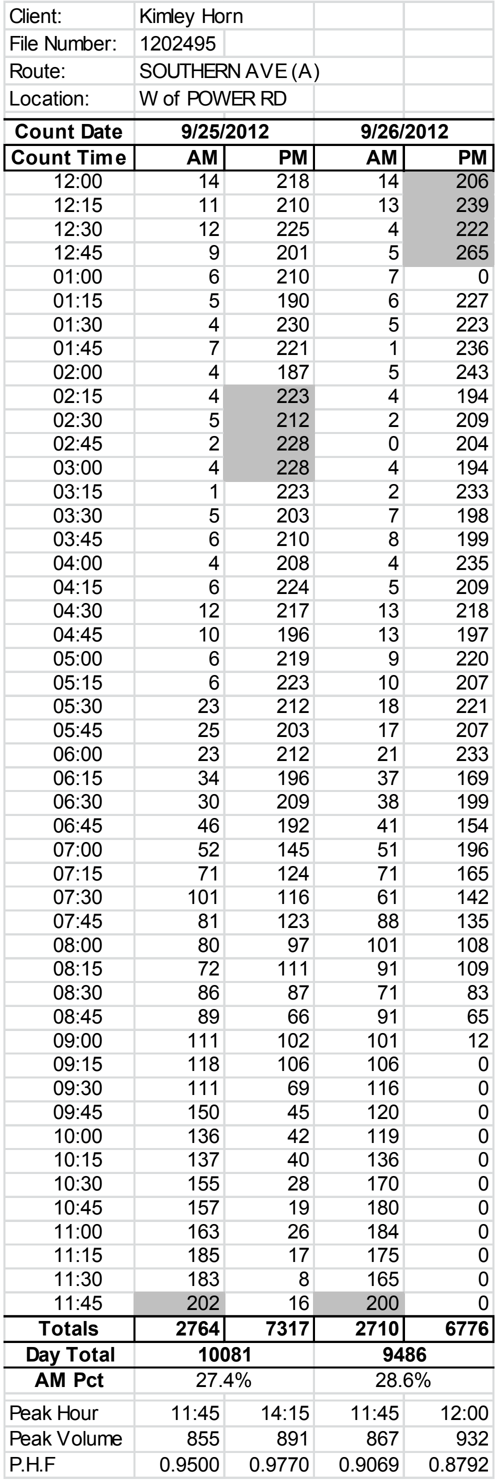
Each probe travel time run will be processed and the trip time and trip delay will be stored in the database for display in the trip selection table. The number of stops, the number of stops per mile, and the average speed metrics will be calculated and stored in the DB. GPS location data that is before the start time location of the trip and GPS location data that is after the end time location of the trip will be deleted for computation of the trip duration, and deleted from the database.

Bluetooth Scanner Data

Bluetooth route travel time data are read from files that are stored by a Bluetooth scanner server in XML format. In this project, a real-time feed was integrated with the system to obtain the files automatically from the Bluetooth vendor’s website. These files are read using a similar import process. These files store individual route travel times in order to compute the average, minimum, and maximum travel times for each time period. Similar to the phase timing data, at the time of import, the user selects the adaptive ON or OFF state for each file.

Tube Counter Data

Tube counter data are read from files that are stored by a tube counter and exported using a USB memory stick. Typical vendors of traffic count data collection format summary files in various ways, sometimes according to a state or local standard. The particular format (shown in Figure 33) is supported in the input process to ingest traffic counts in 15-minute bins. These files are read using a similar import process. Similar to the phase timing data, at the time of import, the user selects the adaptive ON or OFF state for each file.



Client:	Kimley Horn			
File Number:	1202495			
Route:	SOUTHERN AVE (A)			
Location:	W of POWER RD			
Count Date	**9/25/2012**		**9/26/2012**	
Count Time	**AM**	**PM**	**AM**	**PM**
12:00	14	218	14	206
12:15	11	210	13	239
12:30	12	225	4	222
12:45	9	201	5	265
01:00	6	210	7	0
01:15	5	190	6	227
01:30	4	230	5	223
01:45	7	221	1	236
02:00	4	187	5	243
02:15	4	223	4	194
02:30	5	212	2	209
02:45	2	228	0	204
03:00	4	228	4	194
03:15	1	223	2	233
03:30	5	203	7	198
03:45	6	210	8	199
04:00	4	208	4	235
04:15	6	224	5	209
04:30	12	217	13	218
04:45	10	196	13	197
05:00	6	219	9	220
05:15	6	223	10	207
05:30	23	212	18	221
05:45	25	203	17	207
06:00	23	212	21	233
06:15	34	196	37	169
06:30	30	209	38	199
06:45	46	192	41	154
07:00	52	145	51	196
07:15	71	124	71	165
07:30	101	116	61	142
07:45	81	123	88	135
08:00	80	97	101	108
08:15	72	111	91	109
08:30	86	87	71	83
08:45	89	66	91	65
09:00	111	102	101	12
09:15	118	106	106	0
09:30	111	69	116	0
09:45	150	45	120	0
10:00	136	42	119	0
10:15	137	40	136	0
10:30	155	28	170	0
10:45	157	19	180	0
11:00	163	26	184	0
11:15	185	17	175	0
11:30	183	8	165	0
11:45	202	16	200	0
Totals	**2764**	**7317**	**2710**	**6776**
Day Total	**10081**		**9486**	
AM Pct	27.4%		28.6%	
Peak Hour	11:45	14:15	11:45	12:00
Peak Volume	855	891	867	932
P.H.F	0.9500	0.9770	0.9069	0.8792

Figure 33. Table. Sample Traffic Counter Data Format.
(Source: Kimley-Horn and Associates, Inc.)

Phase Timing and Detector Data

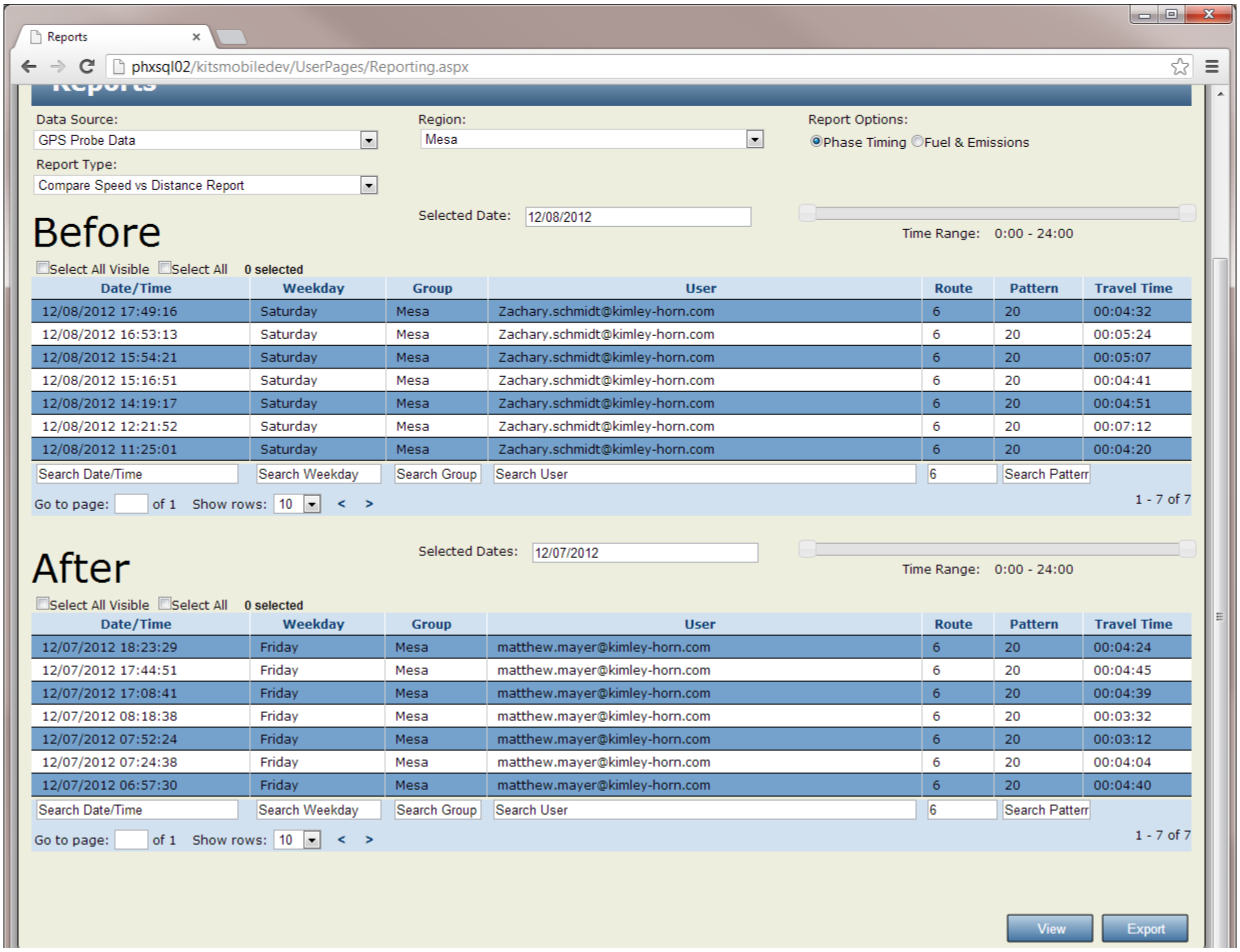
Cycle-by-cycle phase durations for each phase at each intersection and stored in a new database table. Similarly, detector data will be consolidated into cyclic format and stored in a new database table. GOR and V/C will be computed for each phase for each cycle. Arrivals on green and platoon ratio will be calculated using detectors assigned to this MOE for coordinated phases. The pattern number in effect at the intersection closest to the probe trip starting point will be applied to GPS probe trips. The pattern number at the beginning of the trip will be used if two patterns are in effect during a trip.

The remaining MOEs will be calculated when a comparison report is requested by the user:

- Travel time reliability metrics.
- Phase reliability metrics.
- Statistical significance calculations.

BEFORE AND AFTER COMPARISONS FOR VALIDATION OF OPERATIONAL OBJECTIVES

Validation of an operational objective requires comparison of the performance data characterizing the performance of the systems before and after the application of new operational strategies. For this project the before condition is indicative of non-adaptive operation while the after condition is indicative of active ASCT operation. The before condition is used to establish a baseline operation against which the after, or ASCT active operation, can be compared. For each of the data sources, this is implemented as a table-driven selection system as shown in Figure 34.



Data Source: GPS Probe Data

Region: Mesa

Report Options: ● Phase Timing ○ Fuel & Emissions

Report Type: Compare Speed vs Distance Report

Before

Selected Date: 12/08/2012

Time Range: 0:00 - 24:00

☐ Select All Visible ☐ Select All **0 selected**

Date/Time	Weekday	Group	User	Route	Pattern	Travel Time
12/08/2012 17:49:16	Saturday	Mesa	Zachary.schmidt@kimley-horn.com	6	20	00:04:32
12/08/2012 16:53:13	Saturday	Mesa	Zachary.schmidt@kimley-horn.com	6	20	00:05:24
12/08/2012 15:54:21	Saturday	Mesa	Zachary.schmidt@kimley-horn.com	6	20	00:05:07
12/08/2012 15:16:51	Saturday	Mesa	Zachary.schmidt@kimley-horn.com	6	20	00:04:41
12/08/2012 14:19:17	Saturday	Mesa	Zachary.schmidt@kimley-horn.com	6	20	00:04:51
12/08/2012 12:21:52	Saturday	Mesa	Zachary.schmidt@kimley-horn.com	6	20	00:07:12
12/08/2012 11:25:01	Saturday	Mesa	Zachary.schmidt@kimley-horn.com	6	20	00:04:20
Search Date/Time	Search Weekday	Search Group	Search User	6	Search Patterr	

Go to page: of 1 Show rows: 10 < > 1 - 7 of 7

After

Selected Dates: 12/07/2012

Time Range: 0:00 - 24:00

☐ Select All Visible ☐ Select All **0 selected**

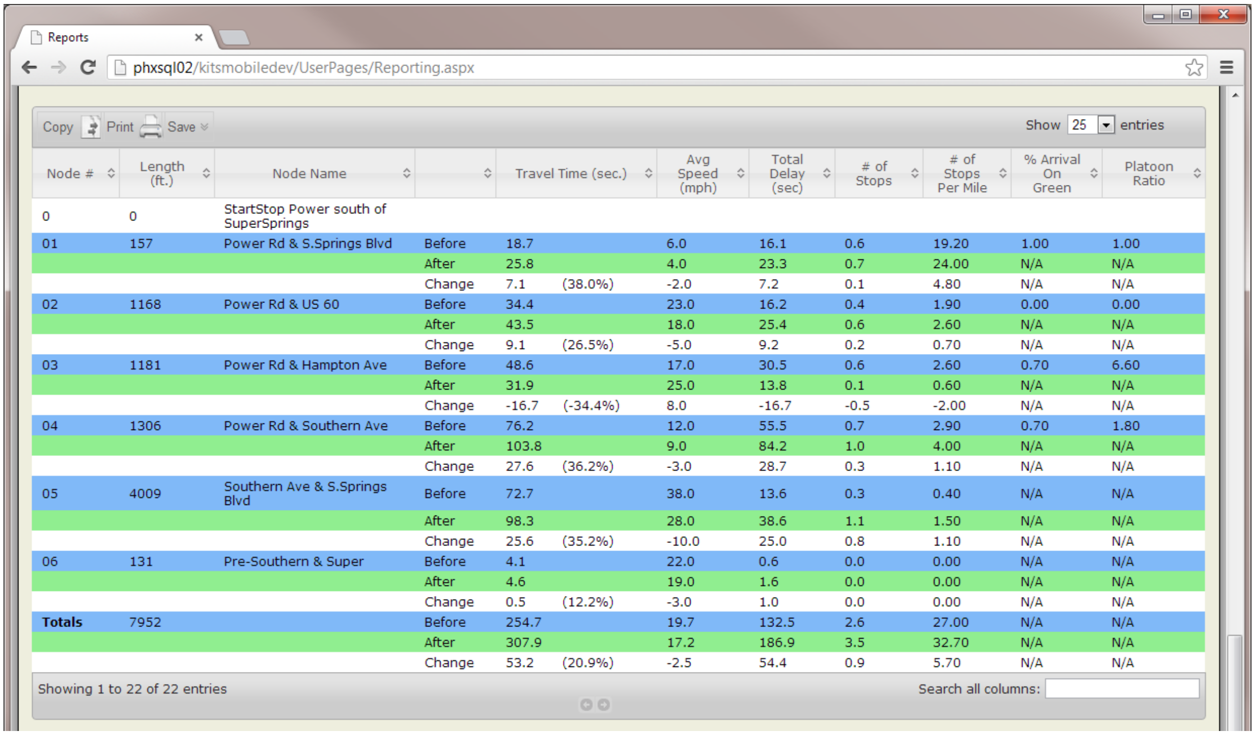
Date/Time	Weekday	Group	User	Route	Pattern	Travel Time
12/07/2012 18:23:29	Friday	Mesa	matthew.mayer@kimley-horn.com	6	20	00:04:24
12/07/2012 17:44:51	Friday	Mesa	matthew.mayer@kimley-horn.com	6	20	00:04:45
12/07/2012 17:08:41	Friday	Mesa	matthew.mayer@kimley-horn.com	6	20	00:04:39
12/07/2012 08:18:38	Friday	Mesa	matthew.mayer@kimley-horn.com	6	20	00:03:32
12/07/2012 07:52:24	Friday	Mesa	matthew.mayer@kimley-horn.com	6	20	00:03:12
12/07/2012 07:24:38	Friday	Mesa	matthew.mayer@kimley-horn.com	6	20	00:04:04
12/07/2012 06:57:30	Friday	Mesa	matthew.mayer@kimley-horn.com	6	20	00:04:40
Search Date/Time	Search Weekday	Search Group	Search User	6	Search Patterr	

Go to page: of 1 Show rows: 10 < > 1 - 7 of 7

Figure 34. Screen Shot. Report Selection Dialog for Before and After Comparison.
(Source: Kimley-Horn and Associates, Inc.)

The analyst can choose from date, day of week, time of day, route number, and pattern number to compare performance. In this example, route 6 runs are being compared for runs on Friday, December 7 (Adaptive ON) versus Saturday, December 8 (Adaptive OFF). Typing the requested route number in the search box below the route column removes all of the other routes from the resulting table so that only trips on route 6 are compared. Pressing "view" results in a table that compares the performance of Before and After conditions. Pressing "Export" will save the page as shown to an excel format for additional graphing or analysis.

A link-by-link performance report is then shown that compares the "before" with the "after" data for the metrics, as shown in Figure 35. The resulting average values for the MOEs and the comparison between before and after is shown for each link. In addition, for this particular report for probe travel runs, if corresponding percent arrivals on green and platoon ratio data are available from the controller for that link, it is also displayed in the row. This part of the results page can be printed or saved to CSV, XLS, or PDF formats. Similar comparison reports are available for phase timing data, route travel times from Bluetooth detectors, and traffic counters.



Node #	Length (ft.)	Node Name		Travel Time (sec.)		Avg Speed (mph)	Total Delay (sec)	# of Stops	# of Stops Per Mile	% Arrival On Green	Platoon Ratio
0	0	StartStop Power south of SuperSprings									
01	157	Power Rd & S.Springs Blvd	Before	18.7		6.0	16.1	0.6	19.20	1.00	1.00
			After	25.8		4.0	23.3	0.7	24.00	N/A	N/A
			Change	7.1	(38.0%)	-2.0	7.2	0.1	4.80	N/A	N/A
02	1168	Power Rd & US 60	Before	34.4		23.0	16.2	0.4	1.90	0.00	0.00
			After	43.5		18.0	25.4	0.6	2.60	N/A	N/A
			Change	9.1	(26.5%)	-5.0	9.2	0.2	0.70	N/A	N/A
03	1181	Power Rd & Hampton Ave	Before	48.6		17.0	30.5	0.6	2.60	0.70	6.60
			After	31.9		25.0	13.8	0.1	0.60	N/A	N/A
			Change	-16.7	(-34.4%)	8.0	-16.7	-0.5	-2.00	N/A	N/A
04	1306	Power Rd & Southern Ave	Before	76.2		12.0	55.5	0.7	2.90	0.70	1.80
			After	103.8		9.0	84.2	1.0	4.00	N/A	N/A
			Change	27.6	(36.2%)	-3.0	28.7	0.3	1.10	N/A	N/A
05	4009	Southern Ave & S.Springs Blvd	Before	72.7		38.0	13.6	0.3	0.40	N/A	N/A
			After	98.3		28.0	38.6	1.1	1.50	N/A	N/A
			Change	25.6	(35.2%)	-10.0	25.0	0.8	1.10	N/A	N/A
06	131	Pre-Southern & Super	Before	4.1		22.0	0.6	0.0	0.00	N/A	N/A
			After	4.6		19.0	1.6	0.0	0.00	N/A	N/A
			Change	0.5	(12.2%)	-3.0	1.0	0.0	0.00	N/A	N/A
Totals	7952		Before	254.7		19.7	132.5	2.6	27.00	N/A	N/A
			After	307.9		17.2	186.9	3.5	32.70	N/A	N/A
			Change	53.2	(20.9%)	-2.5	54.4	0.9	5.70	N/A	N/A

Showing 1 to 22 of 22 entries

Figure 35. Screen Shot. Sample Link by Link Travel Time and Delay Comparison Table.
(Source: Kimley-Horn and Associates, Inc.)

RELIABILITY ESTIMATION

Figure 36 illustrates the reliability measures that are computed for GPS probes and Bluetooth pairs. Average and standard deviation of travel time as well as buffer and planning indices are computed. Buffer time is computed from the 95th percentile, travel time when there are a minimum of 5 data points in a summary bin. If there are fewer than 5 measurements, the buffer time and planning times will be reported as “N/A”. If there are more than 5 measurements, they are ordered by duration and the observations closest to the 95th percentile are averaged to obtain the 95th percentile value. If a specific observation is the 95th percentile observation, then that value is used. For example, if there are exactly 20 measurements, then the 19th slowest travel time is the 95th percentile. If there are 10 measurements, then the average of the 9th and 10th slowest travel times is used as the 95th percentile travel time.

Time Division: 3 hours

Time	Average TT Before	Average TT After	Std Dev TT Before	Std Dev TT After	TT Buffer Index Before	TT Buffer Index After	TT Planning Index Before	TT Planning Index After
12:00 am	00:00:00	00:00:00	00:00:00	00:00:00	0.00	0.00	1.00	1.00
3:00 am	00:00:00	00:00:00	00:00:00	00:00:00	0.00	0.00	1.00	1.00
6:00 am	00:00:00	00:03:52	00:00:00	00:00:33	0.00	0.21	1.00	1.21
9:00 am	00:04:20	00:00:00	00:00:00	00:00:00	0.66	0.00	1.66	1.00
12:00 pm	00:06:01	00:00:00	00:01:10	00:00:00	0.20	0.00	1.20	1.00
3:00 pm	00:04:56	00:04:35	00:00:20	00:00:03	0.46	0.02	1.46	1.02
6:00 pm	00:00:00	00:04:24	00:00:00	00:00:00	0.00	0.06	1.00	1.06
9:00 pm	00:00:00	00:00:00	00:00:00	00:00:00	0.00	0.00	1.00	1.00

Showing 1 to 8 of 8 entries

Figure 36. Screen Shot. Sample Travel Time Reliability Display.
(Source: Kimley-Horn and Associates, Inc.)

For variability estimation of phase data, the following metrics will be computed for each selected time period:

- Maximum value.
- Minimum value.
- Standard deviation.

Maximum, minimum, and standard deviation will be computed for:

- Percent arrivals on green, per link.
- Platoon ratio, per link.
- GOR per phase.
- V/C ratio per phase.

THROUGHPUT MEASUREMENT

Two measures related to throughput estimation will be provided. The first is the vehicles processed by the “before” and “after” systems at each volume count point over a given time period. The analyst will select the time period, and the system will compute:

- Average throughput by count location.
- Maximum, minimum, and standard deviation by count location.
- Maximum, minimum and standard deviation calculations will assume that multiple days of “before” and “after” conditions are available in the database.
- The second measure of throughput is the time to process a given number of vehicles at a given count point. The analyst will specify a given total volume and a start time. The system will compute the time duration from the start time to process the given volume:
  - Average, maximum, minimum, and standard deviation of time to process given volume.
  - Maximum, minimum and standard deviation calculations will assume that multiple days of “before” and “after” conditions are available in the database.

STATISTICAL SIGNIFICANCE COMPUTATIONS

For all MOEs statistical significance computations need to be made and displayed to determine the strength of comparisons between before and after conditions for the purpose of validation. The statistical significance values will include display of whether or not the finding is statistically significant at a 95 percent confidence level and at what acceptance level the finding is significant. On a measure by measure basis, the comparison may need to use nonparametric statistical tests that are ***not*** based on assumptions of normality. In particular, since travel time has known lower bounds (assuming lawful driving) a travel time performance curve may be better estimated by using signed rank comparison tests rather than t-tests.

SUMMARY

The MOE computation and validation tools are a combination of:

- Manually-driven import processes;
- Automated MOE calculations; and
- Manually-driven reporting and analysis actions.

These functions are all implemented as a web-based system using .NET tools. These tools were developed to convert the basic data from the four sources into information for use in validation of operational objectives. Additional functionality was implemented using the Excel PivotTable and PivotChart features to provide graphical outputs in the subsequent sections. The next chapter discusses the field site and data collection process used for testing the validation system.

APPENDIX C. FIELD TESTING OF THE VALIDATION METHODOLOGY

The following chapter discusses the site location and the data collection sites for testing the validation methodology. A small field test site in Mesa, Arizona was chosen as the location for testing the validation approach with a live ASCT that met the budgetary and schedule requirements of the project. This ASCT had been evaluated by others in early 2012, so the city felt comfortable using the validation system and equipment since the results of that evaluation showed reasonable operation of both the ASCT and coordinated plan operation. The implementation of an "ON" and "OFF" study was also not a political concern of the city, although staff did not feel comfortable creating virtual incident conditions to test the responsiveness of the ASCT to anomalies.

SITE LOCATION

The test site location is near Superstition Springs Center mall in Mesa, Arizona. The site intersections are located along Power Road and Southern Avenue. Power Road is a north-south arterial on the east side of the mall and Southern Avenue is an east-west arterial on the north side of the mall. Power road crosses U.S. 60 south of the mall. U.S. 60 is a major east-west freeway in the Phoenix area. Superstition Springs Boulevard connects with both Southern and Power roads in the Northwest corner of the mall and south of U.S. 60 on the southeast corner of the study area, respectively. See Figure 37 below for an aerial view of the test site location.

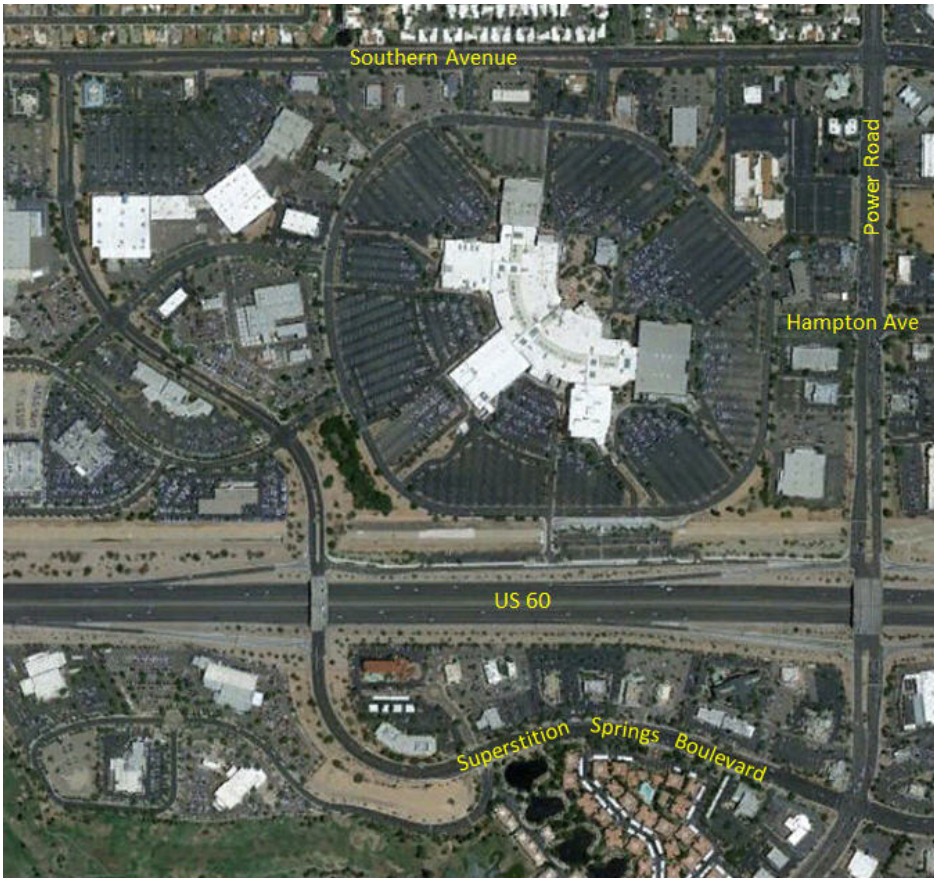


Figure 37. Map. Test Site Location.
(Source: Google maps, USGS, Digital Globe, U.S. Farm Service Agency.)

SITE CHARACTERISTICS

The test site location experiences high traffic volumes due to access provided to the U.S. 60 freeway from communities to the north and the commercial shopping area anchored by the Superstition Springs Center mall. Both Power Road and Southern Avenue are six-lane arterials with a raised median with curb cuts for left turns at intersections and at major un-signalized entrances to the shopping mall. The City of Mesa primarily desires to provide access equity to and from the mall while at the same time providing a pipeline operation to and from U.S. 60 along Power road. The city's installation of the ASCT was initially driven by the fluctuations of traffic during seasonal changes attributable to an increase in winter visitors to the region, the school calendar, and the mall.

As discussed in Chapters 5 and 6, some findings may be less compelling due to the limited project size. In particular, travel time runs are relatively short so some comparison results (e.g. buffer times) are amplified. In particular, this highlights the general conclusion of the project that the community should strive to minimize the use of percentages for reporting validation findings.

LOCATION OF TRAFFIC SIGNALS

There are eleven signalized intersections within the test site. The following five traffic signals were enabled for phase and detector data logging in this analysis:

1. Southern Avenue and Superstition Springs Boulevard.
2. Power Road and Southern Avenue.
3. Power Road and Hampton Road.
4. Power Road and U.S. 60.
5. Power Road and Superstition Springs Boulevard.

Figure 38 below shows the location of each of the traffic signals. Power Road and Southern Avenue and Power Road and the U.S. 60 interchange are the critical locations in the system. The signals where high-resolution phase and detector data were not collected are also operated in adaptive mode by the ASCT. An additional 10 intersections outside the study area are also operated by the ASCT but were not studied in this test.

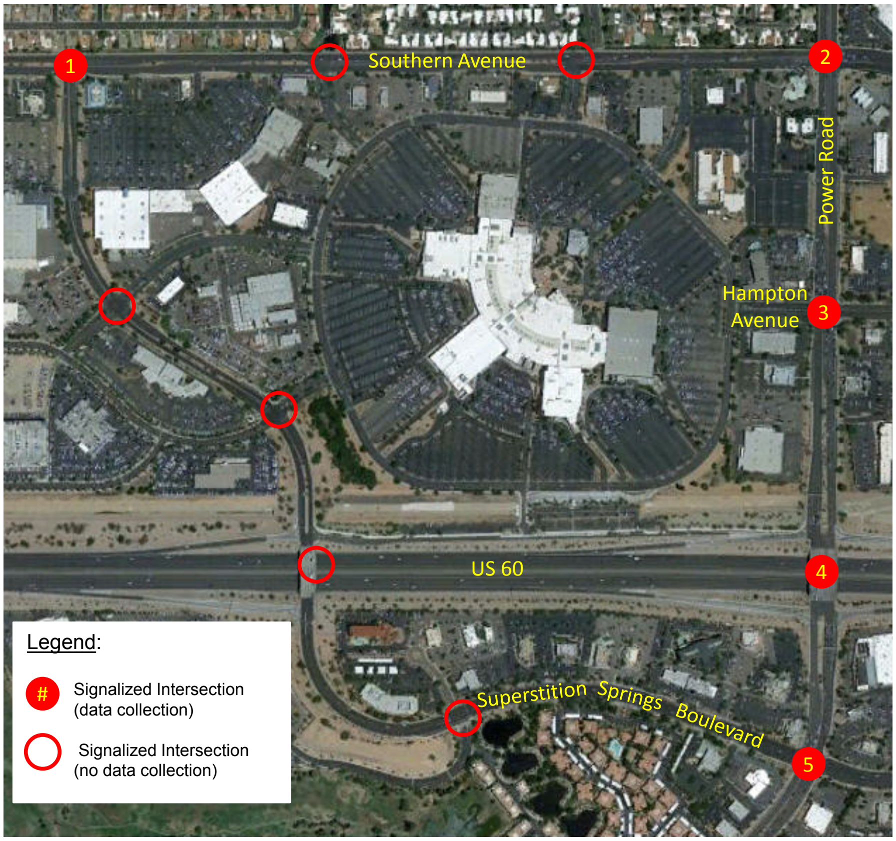


Figure 38. Map. Test Site Traffic Signals.
(Source: Google maps, USGS, Digital Globe, U.S. Farm Service Agency.)

CHARACTERISTICS OF BASELINE TRAFFIC SIGNAL OPERATION

The existing City of Mesa coordinated traffic signal timing plans were used as a baseline comparison for the adaptive operation measures of effectiveness. There were three coordinated time-of-day timing patterns in operation. Table 2 below indicates the pattern schedule.

Table 9. Coordinated Timing Pattern Schedule.

Intersection(s)	Day	Time		Pattern
		Start	End	
1 – Southern Ave and Superstition Springs Blvd	Monday-Friday	12 am	6:30 am	10
		6:30 am	6:30 pm	20
		6:30 pm	12 am	10
2 – Power Rd and Southern Ave 3 – Power Rd and Hampton Ave 4 – Power Rd and U.S. 60 5 – Power Rd and Superstition Springs Blvd	Monday-Friday	12 am	6:30 am	10
		6:30 am	3 pm	20
		3 pm	6:30 pm	30
		6:30 pm	12 pm	10
1 – Southern Ave and Superstition Springs Blvd 2 – Power Rd and Southern Ave 3 – Power Rd and Hampton Ave 4 – Power Rd and U.S. 60 5 – Power Rd and Superstition Springs Blvd	Saturday	12 am	9:30 am	10
		9:30 am	6 pm	20
		6 pm	12 am	10
	Sunday	All Day		10

For Intersection 1 at Southern Avenue and Superstition Springs Boulevard, the time-of-day timing includes an off-peak (night) and a peak (day) pattern schedule for weekdays and Saturday. The off-peak pattern is in operation all day on Sundays.

For the other four site intersections, Intersections 2 through 5, the time-of-day timing includes an off-peak, morning/mid-day peak, and afternoon peak pattern schedule for weekdays. The same off-peak and peak pattern schedule that Intersection 1 utilizes on Saturday and Sunday is also used for Intersections 2 through 5 on weekends. The other signals in the study area follow these patterns as well. Plans 10 and 20 utilize a 100 second cycle time and Plan 30 uses a 110 second cycle time.

DETECTION LAYOUT

The City of Mesa uses a common phase and detector numbering scheme as shown in Figure 39. For example, phases 2 and 6 are always west and eastbound travel directions, respectively. Coordinated phases are varied by pattern if necessary. At all times of day and days of week in this test site, phases 4 and 8 are the coordinated phases on all intersections on Power Road. The ASCT used in this location uses only stop bar detection for adaptive operation. Each detector is 15 feet long and the trailing edge is four feet upstream of the stop bar. At Power Road and Southern Avenue, setback loops are also installed for collecting system detection data. These detectors are appropriate for computation of percent arrivals on green and platoon ratio. No other intersections in the study area have set back loops or detection zones.

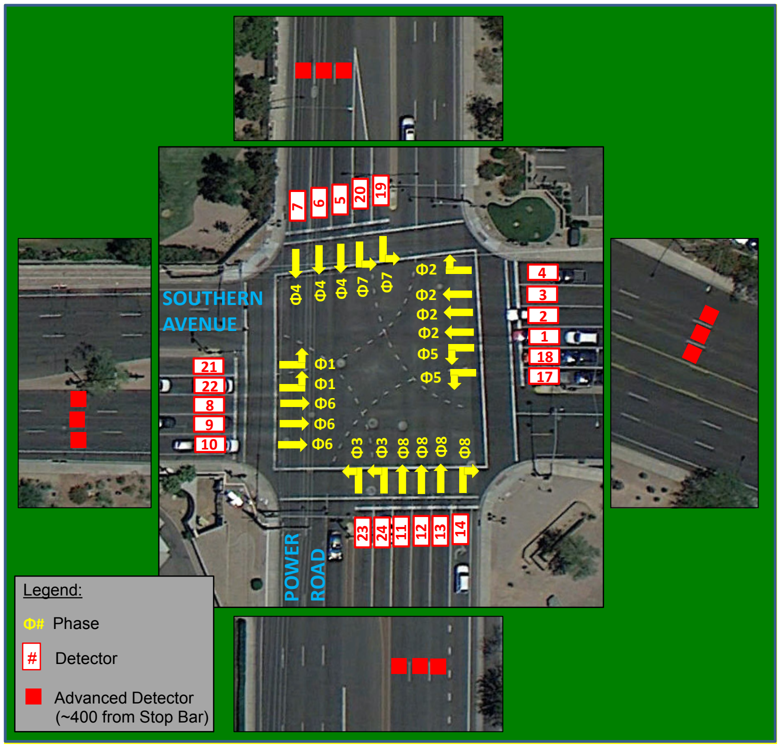


Figure 39. Diagram. Detector Configuration and Phasing.
(Source: Kimley-Horn and Associates, Inc.)

CHARACTERISTICS OF ADAPTIVE TRAFFIC SIGNAL OPERATION

The ASCT deployed in this location controls the durations by sending hold and force-off signals to the NEMA signal controllers over the SDLC bus. All cabinets are TS2. When adaptive control is running, the traffic controllers operate in FREE mode, so coordination is controlled by applying force-offs at the appropriate times. Phase sequence is not modified, but cycle time is allowed to vary at each intersection independently, every cycle. Cycles implemented by the adaptive system tend to hover around the configured coordinated cycle times. An example of the type of cycle variation implemented by the ASCT is provided in Figure 40. This figure illustrates a snapshot of a typical weekday. Similarly, splits are also varied on a cycle-by-cycle basis and tend to vary slightly around their default settings in the coordinated plan. This example shows the average splits for all eight phases implemented by the ASCT on Fridays during the main part of the day.

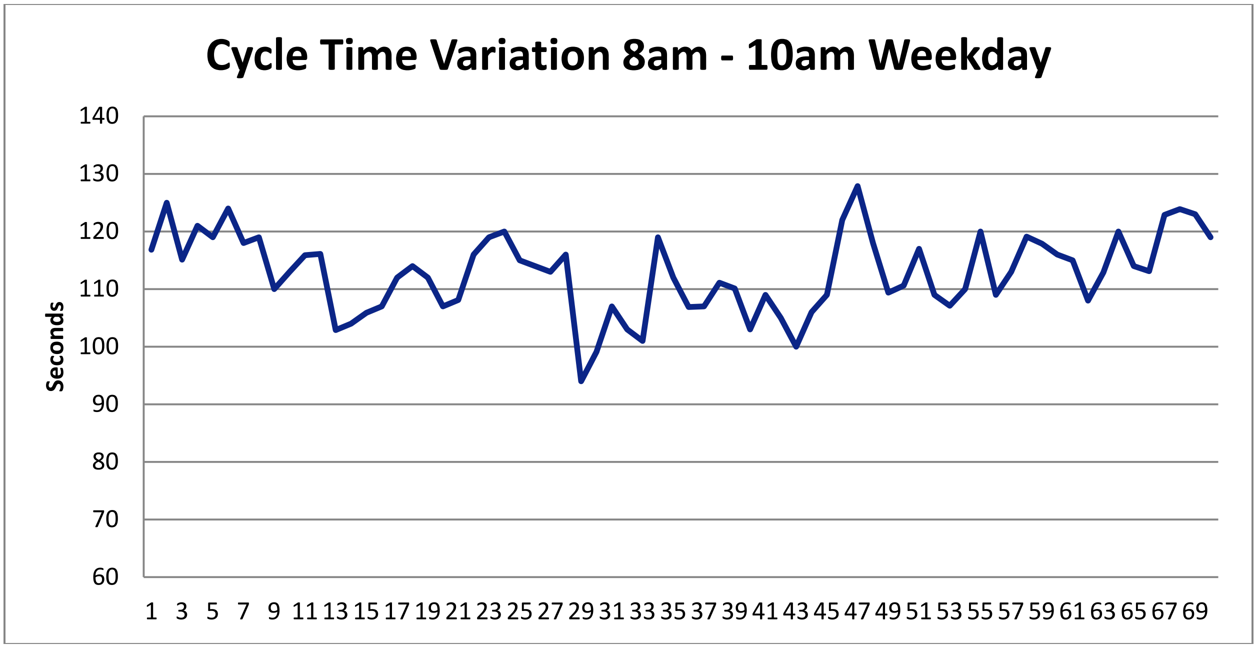


Figure 40. Line Graph. Example ASCT Cycle Adjustment Profile for Power and Southern. (Source: Kimley-Horn and Associates, Inc.)

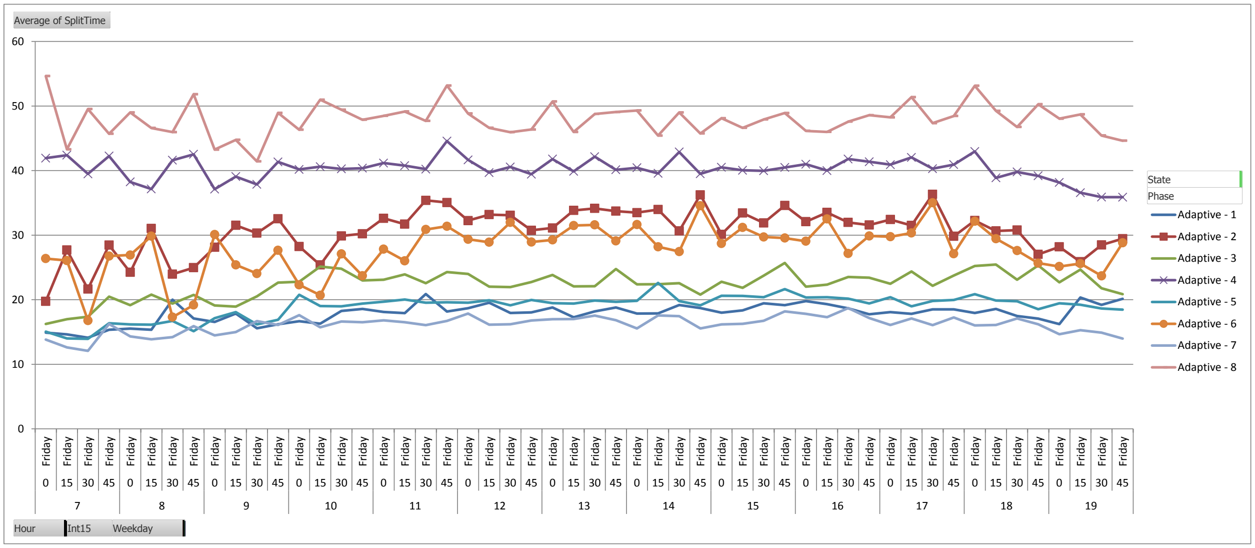


Figure 41. Line Graph. Example ASCT Split Adjustment Profile for Power and Southern (Fridays, 7 am-7 pm). (Source: Kimley-Horn and Associates, Inc.)

LOCATION OF BLUETOOTH DETECTORS

Bluetooth travel time origin and destination detectors were placed at three intersection locations within the test site. Figure 42 shows the locations of the Bluetooth detectors. Each detector was paired with the other two to specify six unique routes:

- North and Southbound on Power Road from Southern to Superstition Springs (Pairs 1 and 2);
- East to Southbound, and North to Westbound from the Northwest corner to the Southeast corner of the system (upside-down "L" shape routes–Pairs 3 and 4); and
- East and Westbound on Southern from Superstition Springs to Power Road (Pairs 5 and 6).

Superstition Springs Boulevard intersects with both Power and Southern. This provides two alternative paths between the two locations at the northwest and southeast corners of the study area. It is not a particularly common route, as many 15-minute periods have no identified trips between the two locations. Based on qualitative analysis of the route travel time data, it is somewhat more common that drivers traverse southeast from Southern and Superstition Springs to Power and Superstition Springs (on either path) than vice versa.

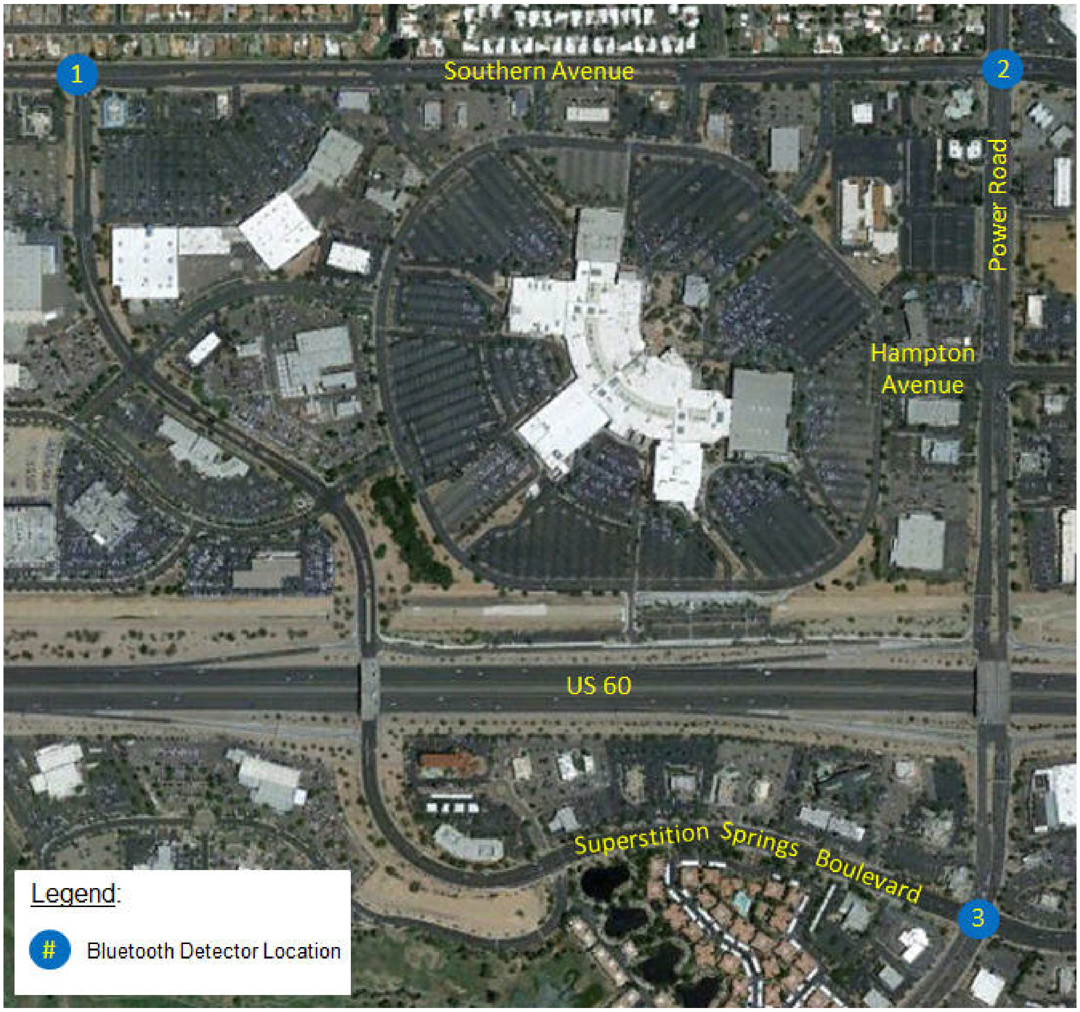


Figure 42. Map. Bluetooth Detector Locations.
(Source: Google maps, USGS, Digital Globe, U.S. Farm Service Agency.)

LOCATION OF 24-HOUR TUBE COUNTERS

Twenty-four-hour traffic volume counts were collected in four locations within the test site. The locations are described below and displayed in Figure 43. Both directions of travel were measured at each counter location.

A. Southern Avenue west of Power Road.
B. Southern Avenue east of Power Road.
C. Power Road south of Southern Avenue.
D. Power Road south of Superstition Springs Boulevard.

These volume counts were used to compare the route travel times with the level of traffic volume, and also to compare the throughput of the ASCT versus the coordinated operation. Traffic counter "C" is the critical location as it measures flows to and from the freeway.

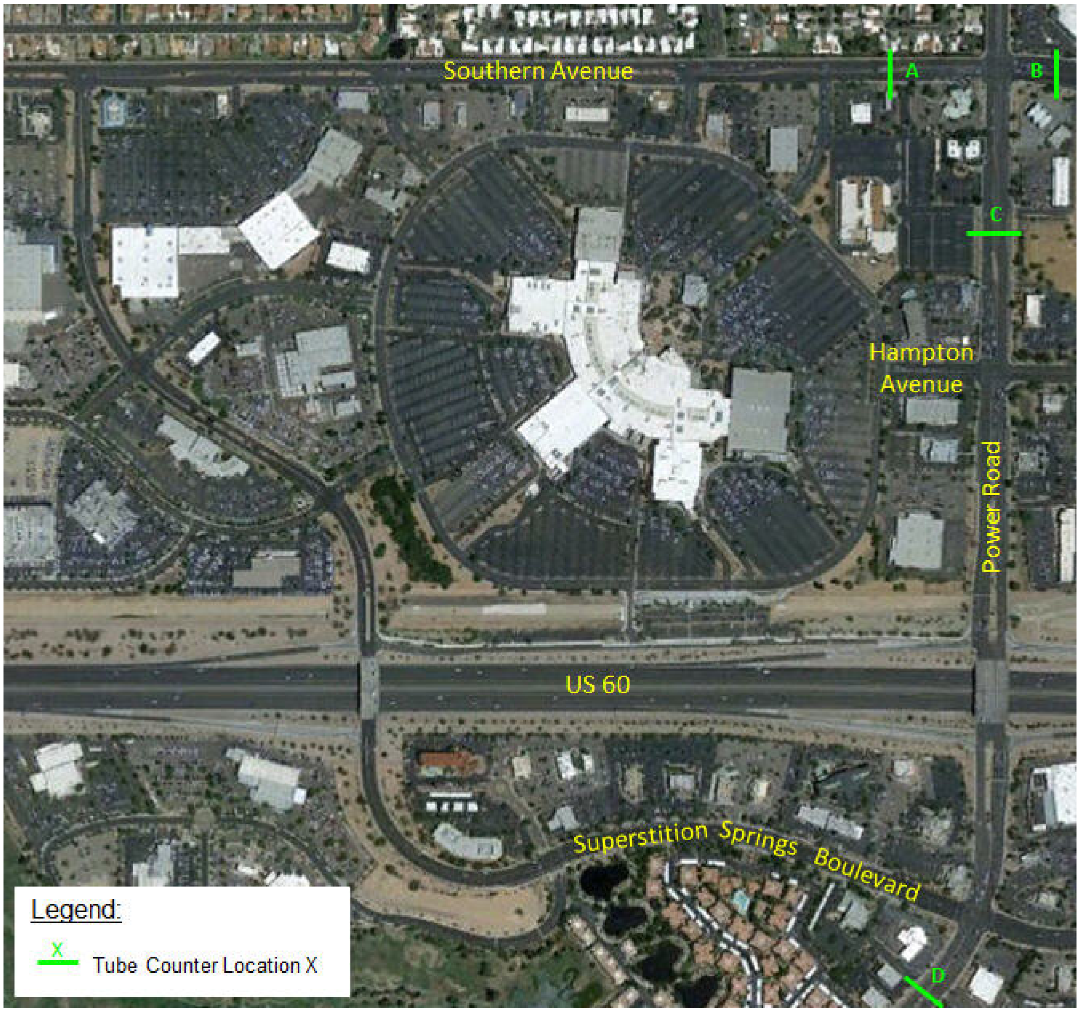


Figure 43. Map. 24-Hour Tube Count Locations.
(Source: Google maps, USGS, Digital Globe, U.S. Farm Service Agency.)

The 24-hour traffic volume counts were collected over a period of 13 weeks from September to December 2012. No data were collected from October 23rd through November 15th. As is quite common in volume data collection studies that have significant duration, there were a variety of issues with the volume counts, ranging from destruction of the tube equipment due to street sweeping to unexplainable gaps in the data collection for one or more counters.

PROBE TRAVEL TIME ROUTES

The Android GPS probe data collection tool was used to complete probe travel time runs using the floating car technique. Eight routes were traversed along Southern Avenue, Superstition Spring Boulevard, and Power Road. The routes are described below and shown in Figure 44.

1. Eastbound Southern Avenue from Superstition Springs Boulevard to Power Road.
2. Westbound Southern Avenue from Power Road to Superstition Springs Boulevard.
3. South-eastbound Superstition Springs Boulevard from Southern Avenue to Power Road.

4. North-westbound Superstition Springs Boulevard from Power Road to Southern Avenue.
5. Eastbound Southern Avenue to Southbound Power Road between Superstition Springs Boulevard intersections.
6. Northbound Power Road to Westbound Southern Avenue between Superstition Springs Boulevard intersections.
7. Southbound Power Road from Southern Avenue to Superstition Springs Boulevard.
8. Northbound Power Road from Superstition Springs Boulevard to Southern Avenue.

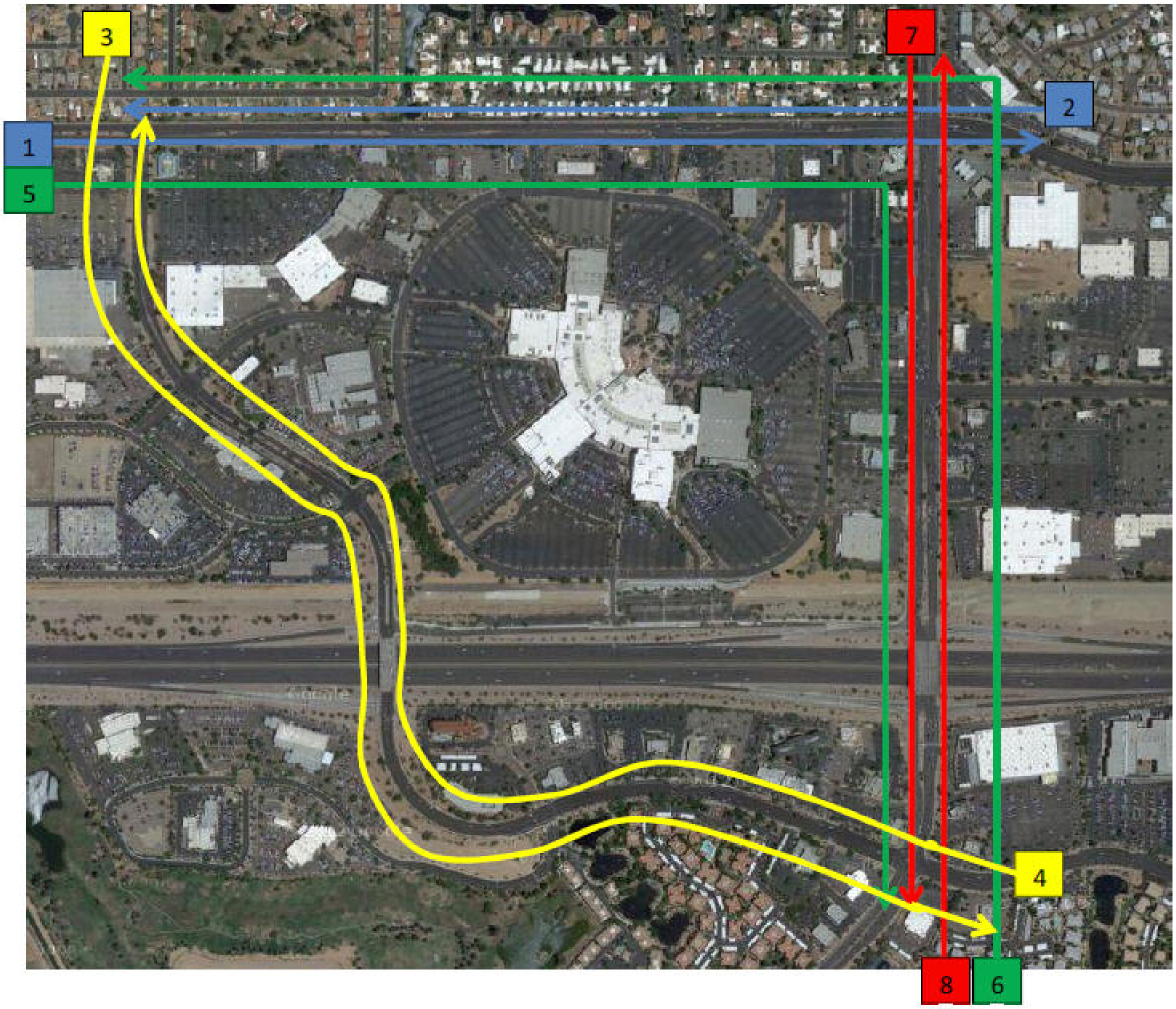


Figure 44. Map. Probe Travel Time Routes.
(Source: Google maps, USGS, Digital Globe, U.S. Farm Service Agency.)

The probe travel time runs were completed over a two week period. Table 10 displays the schedule for execution of the probe travel time runs. Data regarding approximately 24 travel time runs, three for each route, were collected for each two-hour peak period and during some off-peak times. Probe travel runs are quite expensive, which is one reason why the supplementary route travel times and high-resolution phase and detector data are critical to the analysis approach and a key recommendation resulting from this project. As stated earlier in the chapter, it is imperative that travel time runs start significantly upstream of the first intersection in the system and end after clearing the last intersection on the route.

Table 10. Probe Travel Time Schedule.

Day of the Week	**Dates**	**Peak Period**	**Time**
Tuesday	11/27, 12/4	Mid-Day PM	11 am – 1 pm, 4:30 pm – 6:30 pm
Thursday	11/29, 12/6	Mid-Day PM	11 am – 1 pm, 4:30 pm – 6:30 pm
Friday	11/30, 12/7	AM Mid-Day PM	6:30 am – 8:30 am 11 am – 1 pm, 4:30 pm – 6:30 pm
Saturday	12/1, 12/8	Mid-Day PM	11 am – 1 pm, 4:30 pm – 6:30 pm

ADAPTIVE ON/OFF SCHEDULE

For the purpose of this study, the ASCT was turned on and off for randomized periods of time during the validation period. Figure 45 illustrates the days when the ASCT was in operation and when the coordinated timing plans were in operation from September 2012 through December 2012. On the days between 11/23 and 11/26 the ASCT failed due to hardware malfunction. The system is shown in adaptive mode for this period, but it was actually operating the intersections “FREE” at that time.

SEPTEMBER 2012

SUNDAY	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY
						🟩 9/1
🟩 9/2	🟥 9/3	🟥 9/4	🟩 9/5	🟩 9/6	🟥 9/7	🟥 9/8
🟥 9/9	🟩 9/10	🟩 9/11	🟥 9/12	🟥 9/13	🟩 9/14	🟩 9/15
🟩 9/16	🟥 9/17	🟥 9/18	🟩 9/19	🟩 9/20	🟥 9/21	🟥 9/22
🟥 9/23	🟥 9/24	🟥 9/25	🟩 9/26	🟩 9/27	🟩 9/28	🟩 9/29
🟩 9/30						

OCTOBER 2012

SUNDAY	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY
	🟩 10/1	🟥 10/2	🟥 10/3	🟥 10/4	🟩 10/5	🟩 10/6
🟩 10/7	🟩 10/8	🟩 10/9	🟥 10/10	🟥 10/11	🟥 10/12	🟥 10/13
🟥 10/14	🟥 10/15	🟩 10/16	🟩 10/17	🟩 10/18	🟥 10/19	🟥 10/20
🟥 10/21	🟥 10/22	🟩 10/23	🟩 10/24	🟩 10/25	🟩 10/26	🟩 10/27
🟩 10/28	🟩 10/29	🟩 10/30	🟩 10/31			

NOVEMBER 2012

SUNDAY	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY
				🟩 11/1	🟩 11/2	🟩 11/3
🟩 11/4	🟩 11/5	🟩 11/6	🟩 11/7	🟩 11/8	🟩 11/9	🟩 11/10
🟩 11/11	🟩 11/12	🟩 11/13	🟩 11/14	🟩 11/15	🟥 11/16	🟥 11/17
🟥 11/18	🟥 11/19	🟥 11/20	🟥 11/21	🟥 11/22	🟥 11/23	🟥 11/24
🟥 11/25	🟥 11/26	🟥 11/27	🟥 11/28	🟥 11/29	🟩 11/30	

DECEMBER 2012

SUNDAY	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY
						🟩 12/1
🟩 12/2	🟩 12/3	🟩 12/4	🟩 12/5	🟩 12/6	🟥 12/7	🟥 12/8
🟥 12/9	🟥 12/10	🟩 12/11	🟩 12/12	🟩 12/13	🟩 12/14	🟩 12/15
🟩 12/16	🟩 12/17	🟩 12/18	🟩 12/19	🟩 12/20	🟩 12/21	🟩 12/22
🟩 12/23	🟩 12/24	🟩 12/25	🟩 12/26	🟩 12/27	🟩 12/28	🟩 12/29
🟩 12/30	🟩 12/31					

LEGEND:

🟩 SCATS ON
🟥 SCATS OFF

Figure 45. Calendar. ASCT On/Off Schedule.
(Source: Kimley-Horn and Associates, Inc.)

The ASCT was “ON” for the following:

- 8 Sundays
- 7 Mondays
- 8 Tuesdays
- 9 Wednesdays
- 9 Thursdays
- 7 Fridays
- 8 Saturdays

The ASCT was “OFF” for the following:

- 7 Sundays
- 8 Mondays
- 6 Tuesdays
- 5 Wednesdays
- 5 Thursdays
- 7 Fridays
- 7 Saturdays

DATA COLLECTION DISCUSSION

A quality data collection process and validation of raw data are essential to reliable data analysis. This section discusses how the different types of data were collected and prepared for analysis. Figure 46 is a comprehensive schedule showing the data that were collected on each day during the study period. Each row of the schedule represents a different type of data. The top row indicates if the ASCT was ON (green) or OFF (red) on that given day. Data types that are highlighted in a solid color for their row were complete for that given day. Days with incomplete data are not highlighted and days with zero data have no text or color. Due to a variety of real-world hardware and software functionality challenges, as can be seen from the figure, the data are not comprehensive for all data types for the entire period. The Purple color in the ASCT ON/OFF row of the schedule indicate those days when the ASCT was supposed to be on but was failed free due to field equipment failure.

SUNDAY	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY
GREEN SCATS ON / RED SCATS OFF PHASE/TIMING 24 HR TUBE COUNTS [missing data] BLUETOAD TRAVEL TIME	🟩 **8/27**	🟩 **8/28** - 24 hr Tube Counts	🟥 **8/29** - Tube Counts	🟥 **8/30** - Tube Counts [AWB]	🟩 **8/31** - Tube Counts [AWBAM]	🟩 **9/1** - Tube Counts
🟩 **9/2** - Tube Counts [BWBPM]	🟥 **9/3** - Tube Counts [BWB]	🟥 **9/4** - Tube Counts [AWBAM]	🟩 **9/5** - Tube Counts	🟩 **9/6** - Tube Counts	🟥 **9/7** - Tube Counts [DNBM/PM]	🟥 **9/8** - Tube Counts [DNB]
🟥 **9/9** - Tube Counts [DNB]	🟩 **9/10** - Tube Counts [AWBM/PM,DNB]	🟩 **9/11** - Tube Counts [AWB,DNB]	🟥 **9/12** - Tube Counts [AWBAM,DNBAM]	🟥 **9/13** - Phase/Timing Data for Int 3,5 - Tube Counts	🟩 **9/14** - Phase/Timing Data for Int 3,5 - Tube Counts	🟩 **9/15** - Tube Counts
🟩 **9/16**	🟥 **9/17**	🟥 **9/18** - Phase/Timing Data for Int 3,5	🟩 **9/19** - Phase/Timing Data for Int 3,5	🟩 **9/20**	🟥 **9/21**	🟥 **9/22**

SUNDAY	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY
- Tube Counts	- Tube Counts	- Tube Counts	- Tube Counts	- Tube Counts [AWB]	- Tube Counts [AWB]	- Tube Counts [AWB]
9/23 - Tube Counts [AWB]	**9/24** - Phase/Timing Data for Int 1,2 - Tube Counts [AWB]	**9/25** - Phase/Timing Data for Int 1,2 - Tube Counts [AWB]	**9/26** - Tube Counts [AWB,DNBAM/M]	**9/27** - Tube Counts [A]	**9/28** - Tube Counts [A]	**9/29** - Tube Counts [A]
9/30 - Tube Counts [A]	**10/1** - Tube Counts [A]	**10/2** - Phase/Timing Data for Int 3 - Tube Counts [A]	**10/3** - Phase/Timing Data for Int 1,2,5 - Tube Counts [A]	**10/4** - Phase/Timing Data for Int 1,2,5 - Tube Counts [AAM]	**10/5** - Phase/Timing Data - Tube Counts	**10/6** - Phase/Timing Data - Tube Counts
10/7 - Phase/Timing Data - Tube Counts	**10/8** - Phase/Timing Data - Tube Counts	**10/9** - Phase/Timing Data - Tube Counts [A]	**10/10** - Phase/Timing Data - Tube Counts [A]	**10/11** - Phase/Timing Data - Tube Counts [A]	**10/12** - Phase/Timing Data - Tube Counts [A]	**10/13** - Phase/Timing Data - Tube Counts [A]
10/14 - Phase/Timing Data	**10/15** - Phase/Timing Data	**10/16** - Phase/Timing Data	**10/17** - Phase/Timing Data	**10/18** - Phase/Timing Data	**10/19** - Phase/Timing Data	**10/20** - Phase/Timing Data

SUNDAY	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY
- Tube Counts [A]	- Tube Counts [A] - BlueTOAD Data	- Tube Counts [A] - BlueTOAD Data	- Tube Counts [A] - BlueTOAD Data	- Tube Counts [A] - BlueTOAD Data	- Tube Counts [A] - BlueTOAD Data	- Tube Counts [A] - BlueTOAD Data
10/21	**10/22**	**10/23**	**10/24**	**10/25**	**10/26**	**10/27**
- Phase/Timing Data - Tube Counts [A] - BlueTOAD Data	- Phase/Timing Data - Tube Counts [A] - BlueTOAD Data	- Phase/Timing Data - BlueTOAD Data	- Phase/Timing Data - BlueTOAD Data	- Phase/Timing Data - BlueTOAD Data	- Phase/Timing Data - BlueTOAD Data	- Phase/Timing Data - BlueTOAD Data
10/28	**10/29**	**10/30**	**10/31**	**11/1**	**11/2**	**11/3**
- Phase/Timing Data - BlueTOAD Data	- Phase/Timing Data - BlueTOAD Data	- Phase/Timing Data - BlueTOAD Data	- Phase/Timing Data - BlueTOAD Data	- Phase/Timing Data for Int 2,3,4,5 - BlueTOAD Data	- Phase/Timing Data for Int 2,3,4,5 - BlueTOAD Data	- Phase/Timing Data for Int 3,4,5 - BlueTOAD Data
11/4	**11/5**	**11/6**	**11/7**	**11/8**	**11/9**	**11/10**
- Phase/Timing Data for Int 3,4,5 - BlueTOAD Data	- Phase/Timing Data for Int 3,4,5 - BlueTOAD Data	- Phase/Timing Data for Int 3,4,5 - BlueTOAD Data	- Phase/Timing Data for Int 3,4,5 - BlueTOAD Data	- Phase/Timing Data for Int 3,4,5 - BlueTOAD Data	- Phase/Timing Data for Int 3,4,5 - BlueTOAD Data	- Phase/Timing Data for Int 3,4,5 - BlueTOAD Data
11/11	**11/12**	**11/13**	**11/14**	**11/15**	**11/16**	**11/17**

SUNDAY	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY
- Phase/Timing Data for Int 3,4,5 - BlueTOAD Data	- Phase/Timing Data for Int 3,4,5 - BlueTOAD Data	- Phase/Timing Data for Int 3,4,5 - BlueTOAD Data	- Phase/Timing Data for Int 3,4,5 - BlueTOAD Data	- Phase/Timing Data for Int 3,4,5 - Tube Counts [CSB] - BlueTOAD Data	- Phase/Timing Data for Int 3,4,5 - Tube Counts [CSB] - BlueTOAD Data	- Phase/Timing Data for Int 3,4,5 - Tube Counts [CSB] - BlueTOAD Data
11/18	**11/19**	**11/20**	**11/21**	**11/22**	**11/23**	**11/24**
- Phase/Timing Data for Int 3,4,5 - Tube Counts [CSB] - BlueTOAD Data	- Phase/Timing Data for Int 3,4,5 - Tube Counts [CSB] - BlueTOAD Data	- Phase/Timing Data for Int 3,4,5 - Tube Counts [CSBAM] - BlueTOAD Data	- Phase/Timing Data - Tube Counts - BlueTOAD Data	- Phase/Timing Data - Tube Counts - BlueTOAD Data	- Phase/Timing Data - Tube Counts - BlueTOAD Data	- Phase/Timing Data - Tube Counts - BlueTOAD Data
11/25	**11/26**	**11/27**	**11/28**	**11/29**	**11/30**	**12/1**
- Phase/Timing Data - Tube Counts - BlueTOAD Data	- Phase/Timing Data - Tube Counts - BlueTOAD Data	- Phase/Timing Data - Tube Counts - BlueTOAD Data - Travel Time Data	- Phase/Timing Data - Tube Counts - BlueTOAD Data	- Phase/Timing Data - Tube Counts [AWB] - BlueTOAD Data - Travel Time Data	- Phase/Timing Data - Tube Counts [A] - BlueTOAD Data - Travel Time Data	- Phase/Timing Data - Tube Counts [A] - BlueTOAD Data - Travel Time Data
12/2	**12/3**	**12/4**	**12/5**	**12/6**	**12/7**	**12/8**
- Phase/Timing Data	- Phase/Timing Data	- Phase/Timing Data for Int 2,3,4,5	- Phase/Timing Data for Int 2,3,4,5	- Phase/Timing Data for Int 2,3,4,5	- Phase/Timing Data for Int 2,3,4,5	- Phase/Timing Data for Int 2,3,4,5

SUNDAY	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY
- Tube Counts [A, C] - BlueTOAD Data	- Tube Counts [A, C, D] - BlueTOAD Data	- Tube Counts [A, C, D] - BlueTOAD Data - Travel Time Data	- Tube Counts [A, C, D] - BlueTOAD Data	- Tube Counts - BlueTOAD Data - Travel Time Data	- Tube Counts - BlueTOAD Data - Travel Time Data	- Tube Counts - BlueTOAD Data - Travel Time Data
12/9	**12/10**	**12/11**	**12/12**	**12/13**	**12/14**	**12/15**
- Phase/Timing Data for Int 2,3,4,5 - Tube Counts - BlueTOAD Data	- Phase/Timing Data for Int 2,3,4,5 - Tube Counts - BlueTOAD Data	- Phase/Timing Data for Int 2,3,4,5 - Tube Counts - BlueTOAD Data	- Phase/Timing Data for Int 2,3,4,5 - Tube Counts - BlueTOAD Data	- Phase/Timing Data for Int 2,3,4,5 - Tube Counts [BEB, C, DNB] - BlueTOAD Data	- Phase/Timing Data for Int 2,3,4,5 - Tube Counts [BEB, CNB, DNB] - BlueTOAD Data	- Phase/Timing Data for Int 2,3,4,5 - Tube Counts [BEB] - BlueTOAD Data
12/16	**12/17**	**12/18**	**12/19**	**12/20**	**12/21**	**12/22**
- Phase/Timing Data for Int 2,3,4,5 - Tube Counts [BEB] BlueTOAD Data	- Phase/Timing Data for Int 2,3,4,5 - Tube Counts [BEB] BlueTOAD Data	- Phase/Timing Data for Int 2,3,4,5 - Tube Counts [BEB] BlueTOAD Data	- Phase/Timing Data for Int 2,3,4,5 - Tube Counts [BEB] BlueTOAD Data	- Phase/Timing Data for Int 2,3,4,5 BlueTOAD Data	BlueTOAD Data	BlueTOAD Data
12/23	**12/24**	**12/25**	**12/26**	**12/27**	**12/28**	**12/29**
- Phase/Timing Data for Int 2,3,4,5	- Phase/Timing Data for Int 2,3,4,5	- Phase/Timing Data for Int 2,3,4,5	- Phase/Timing Data for Int 2,3,4,5	- Phase/Timing Data for Int 2,3,4,5	- Phase/Timing Data for Int 2,3,4,5	- Phase/Timing Data for Int 2,3,4,5

SUNDAY	**MONDAY**	**TUESDAY**	**WEDNESDAY**	**THURSDAY**	**FRIDAY**	**SATURDAY**
BlueTOAD Data	BlueTOAD Data	BlueTOAD Data	BlueTOAD Data	BlueTOAD Data	BlueTOAD Data	BlueTOAD Data
12/30	**12/31**	**1/1**	**1/2**	**1/3**	**1/4**	**1/5**
- Phase/Timing Data for Int 2,3,4,5	- Phase/Timing Data for Int 2,3,4,5	- Phase/Timing Data for Int 2,3,4,5	- Phase/Timing Data for Int 2,3,4,5	- Phase/Timing Data for Int 2,3,4,5	- Phase/Timing Data for Int 2,3,4,5	- Phase/Timing Data for Int 2,3,4,5
BlueTOAD Data	BlueTOAD Data	BlueTOAD Data	BlueTOAD Data	BlueTOAD Data	BlueTOAD Data	BlueTOAD Data

Figure 46. Schedule. Data Availability Over the Study Period
(Source: Kimley-Horn and Associates, Inc.)

Measures of effectiveness were produced from the data collected and processed into reports using tools available in the validation system. In addition to applying the reporting tools developed for the project, the MOE data were also exported into a comprehensive Excel database and dynamically analyzed using pivot charts. Representative results are presented in Chapter 5.

Phase Timing Data

As discussed, in Chapter 3, raw phase timing and detector actuation data are continuously collected by the ASC/3 controllers operating the test site intersections. These raw binary phase timing data files are retrieved from the intersections using an FTP script and then run through a PHP script that converts the binary into CSV files. The CSV files were then parsed by the import process to the validation website and the MOEs computed. In many cases, as illustrated in Figure 19, missing and incomplete binary files confound the analysis process. Regardless, this source of detailed information from the field controllers is invaluable in reducing the cost of validation and performance measurement analysis. Improvements to these data storage processes on field controllers to improve the reliability or use of third-party devices in locations with obsolete controllers are critical to enhance state of the practice in MOE computation.

Bluetooth Travel Time Data

The Bluetooth travel time data was collected by the detectors and stored by the Bluetooth device vendor at the vendor's website. The Bluetooth readers are connected to the city's IP network. City IT staff allowed the Bluetooth devices to connect to the internet to transmit the vehicle match data for processing. The information was imported to the validation system using an automated download of the Bluetooth travel time data from the vendor website. Similar to some of the challenges of data collection from the field controllers and the tube counters, a variety of real-world issues confounded the collection of the Bluetooth travel times for the first month of the effort. Extending support to additional Bluetooth data collection vendor systems will improve state of the practice in MOE computation.

24-Hour Tube Count Data

The 24-hour tube count data was first reviewed manually to identify collection errors or inconsistencies. Data from several locations were damaged by street sweepers and recorded zero vehicles or a value significant amount less than expected. These invalid data values were removed from the data set and are not included in the analysis. The tube count volume data was summarized in 15 minute intervals and imported into the validation system via the import process. Missing data are marked in Figure 19 in brackets [] with the letter designation of the counter and NB, SB, EB, WB designations if the missing information is isolated to one direction or the other. AM or PM annotations are appended to the letter designation if the missing data are isolated to morning or evening.

Probe Travel Time Data

The probe travel time data are sent automatically via the Android GPS probe data collection app. Each run was reviewed manually to identify any data collection errors or runs where cellular coverage was intermittent. Minor errors such as route mislabeling by the data collectors were repaired manually in the database.

APPENDIX D. MEASURES OF EFFECTIVENESS ANALYSIS AND FINDINGS

After the field data collection efforts were completed and the information was imported to the web system, analysis of the results was completed for each of the data sources. This chapter summarizes the results of the validation tests and presents some representative exhibits that illustrate key outcomes.

GPS PROBE TRAVEL TIME FINDINGS

Probe travel times are the most traditional method of validation of signal timing performance used by the traffic engineering community. As demonstrated in the following exhibits, average performance as recorded by the probe travel time runs does not distinguish between the ASCT operation and coordination for all of the routes. Table 11 summarizes the results for the eight travel routes for travel time, average speed, number of stops per mile, and the buffer time reliability metric for the three time of day periods (AM, PM, off-peak).

Table 11. Travel Time Performance Comparisons For GPS Probe Runs

	Travel Time (Runs Before)	Travel Time (Runs After)	Average Speed (Runs Before)	Average Speed (Runs After)	Stops per Mile (Runs Before)	Stops per Mile (Runs After)	AM Buffer Index (Runs Before)	AM Buffer Index (Runs After)	AM Reliability Difference	Midday Buffer Index (Runs Before)	Midday Buffer Index (Runs After)	Midday reliability difference	PM Buffer Index (Runs Before)	PM Buffer Index (Runs After)	PM Reliability difference
Route 1 (25, 29)	1:58	2:08	33	29	1.2	1.5	0.4	1.3	-0.9	0.3	0.3	0.0	0.2	1.3	-1.0
Route 2 (20, 27)	1:52	2:08	34	29	1	1.34	0.3	0.3	0.0	0.5	0.4	0.1	0.2	0.2	0.0
Route 3 (21, 22)	3:53	3:33	23	26	1.7	1.7	0.4	0.4	0.0	0.3	0.2	0.1	0.5	0.4	0.1
Route 4 (17, 21)	3:20	3:26	40	43	1.7	1.7	0.4	0.4	0.1	0.4	0.4	0.0	0.5	0.4	0.1
Route 5 (24, 27)	5:01	5:12	19	18	1.8	2	1.3	1.0	0.3	0.3	0.5	-0.1	0.6	1.4	-0.9
Route 6 (26, 26)	4:36	4:38	18	17	1.6	2	0.9	0.5	0.3	0.4	0.5	-0.1	0.8	0.5	0.3
Route 7 (27, 28)	2:48	2:55	18	17	2.2	2.1	0.9	1.4	-0.4	0.4	0.8	-0.5	0.2	0.1	0.0
Route 8 (27, 30)	2:39	2:42	18	18	2	2.5	1.4	1.0	0.3	0.4	0.5	-0.1	1.0	0.3	0.7

Figure 47 illustrates the comparison of the average speed versus distance for route #1. Coordinated mode is identified as the “before” condition and adaptive mode is identified as the “after” condition. Similar graphs for the other seven routes are presented in Appendix A.

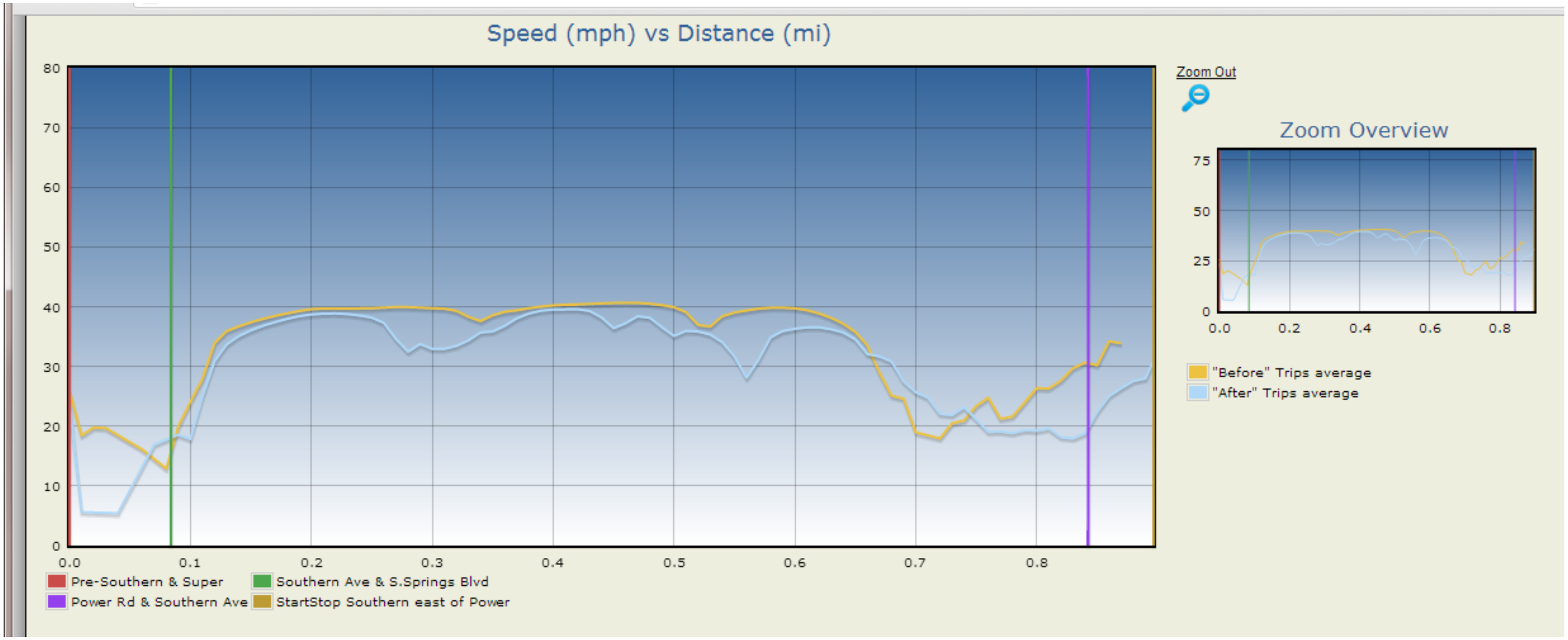


Figure 47. Screen Shot. Comparison of Average Speed for Route 1.
(Source: Kimley-Horn and Associates, Inc.)

Buffer Time Analysis

Figure 48 summarizes the differences between the buffer times for each of the eight routes. The x-axis represents each of the eight routes. The three bars for each route indicate the difference in the buffer time for the AM, mid-day, and PM peak periods. Bars above zero indicate that the ASCT produced more reliable travel times than coordinated operation. Bars below zero indicate that coordinated operation is more reliable than ASCT operation using all of the GPS trips for that time of day for that route.

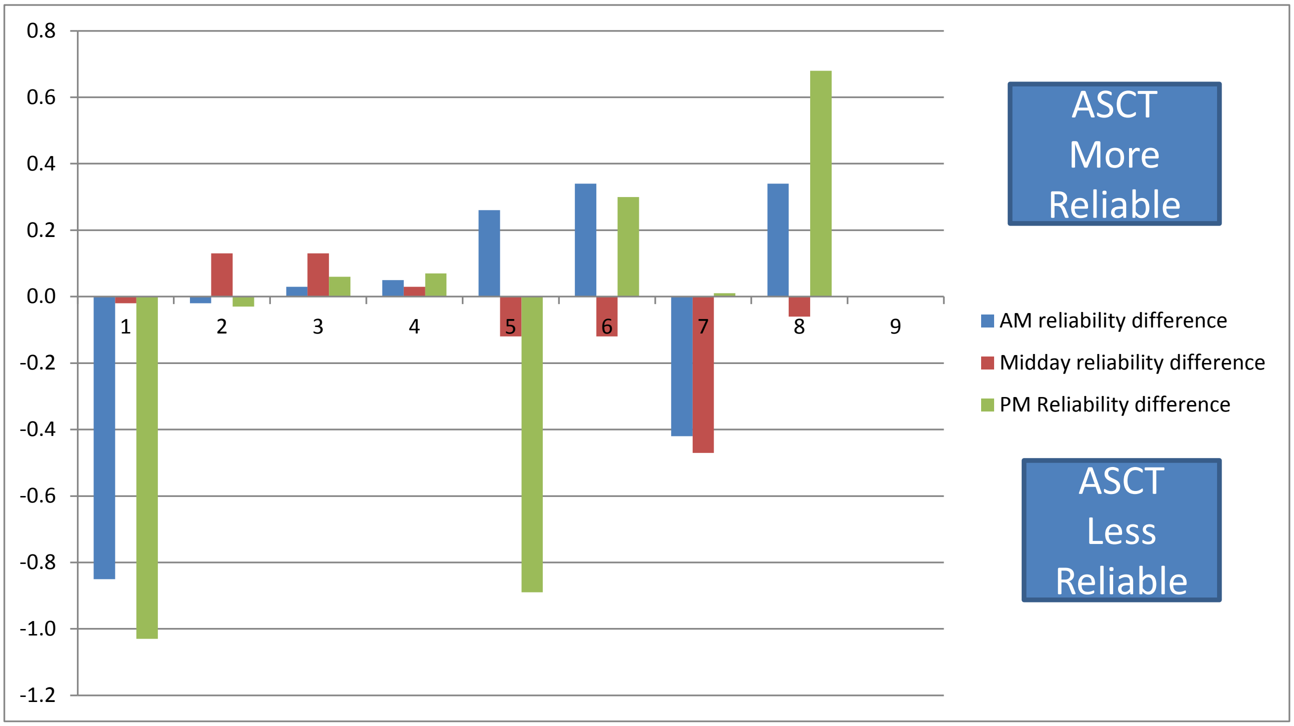


Figure 48. Bar graph. Comparison of Buffer Times for the Eight Routes.
(Source: Kimley-Horn and Associates, Inc.)

Summary of GPS Probe Data Analysis

Table 12 summarizes both the average trip time and reliability performance from a qualitative perspective. As shown in the table, and referring to Figure 17 illustrating the route definitions, there is clearly a difference in the operating principles of coordination and the ASCT with respect to route travel reliability. Routes 1-4 do not manifest this difference, but Routes 5-8 identify a clear difference in the operating principle of the ASCT that is not immediately observable from the average travel times, which are more or less equal. Routes 2 and 3 showed a negligible improvement in the reliability of travel time during the off-peak when ASCT operation was in effect.

Routes 5 and 7 both include the section of Southbound Power Road, and routes 6 and 8 both include the section of northbound Power Road. The results for both pairs of routes indicate higher reliability for southbound travel when the ASCT is operating and higher reliability for northbound travel when in coordination. The city's objective was to provide coordination in both directions, which is not achieved by the ASCT.

Table 12. Qualitative Comparison of Average Trip Time and Reliability – GPS Probe Data

Route	Average Travel Time	Buffer Time	Combined Result
1	Coordination slightly better	Coordination much more reliable	Coordination clearly better
2	Coordination slightly better	ASCT slightly more reliable	Mixed
3	ASCT better	ASCT slightly more reliable	ASCT slightly better
4	No difference	No difference	No difference
5	No difference	Coordination more reliable in mid and PM	ASCT favoring southbound travel on Power at the expense of northbound travel, relative to coordination
6	No difference	ASCT more reliable in AM and PM	ASCT favoring southbound travel on Power at the expense of northbound travel, relative to coordination
7	No difference	Coordination more reliable	ASCT favoring southbound travel on Power at the expense of northbound travel, relative to coordination
8	No difference	ASCT more reliable	ASCT favoring southbound travel on Power at the expense of northbound travel, relative to coordination

FINDINGS USING BLUETOOTH TRAVEL TIME DETECTORS

Over the study period, over 4,000 vehicle re-identifications were recorded for each of the six Bluetooth route pairs almost continuously between October 15th and December 12th. As demonstrated in Table 13, negligible differences in average performance of coordinated and adaptive operation were identified. Figure 49 illustrates that coordination showed somewhat better reliability performance for two of the route pairs (3 and 4) and negligible differences in reliability between the other four route pairs. Note that the average travel time between the pairs is consistently less than the travel time measured using GPS probes. This is likely because the vehicles are identified as soon as they are within GPS range of the destination reader, in effect not including any delays due to queues or signal timing to complete the trip to the other side of the intersection.

Table 13. Summary of Travel Time Reliability Comparisons from 11/4-11/15 (adaptive) versus 11/16-11/21 (Coordination)

	Travel Time AM (Total Observations Before)	**Travel Time AM (Total Observations After)**	**Travel Time Off Peak (Total Observations Before)**	**Travel Time Off Peak (Total Observations After)**	**Travel Time PM (Total Observations Before)**	**Travel Time PM (Total Observations After)**	**AM Buffer Index (Total Observations Before)**	**AM Buffer Index (Total Observations After)**	**AM reliability difference**	**Midday Buffer Index (Total Observations Before)**	**Midday Buffer Index (Total Observations After)**	**Midday reliability difference**	**PM Buffer Index (Total Observations Before)**	**PM Buffer Index (Total Observations After)**	**PM Reliability difference**
Pair 1 (570, 642)	1:58	2:08	33	29	1.2	1.5	0.4	1.3	-0.9	0.3	0.3	0.0	0.2	1.3	-1.0
Pair 2 (567, 653)	1:52	2:08	34	29	1	1.34	0.3	0.3	0.0	0.5	0.4	0.1	0.2	0.2	0.0
Pair 3 (545, 627)	3:53	3:33	23	26	1.7	1.7	0.4	0.4	0.0	0.3	0.2	0.1	0.5	0.4	0.1
Pair 4 (541, 591)	3:20	3:26	40	43	1.7	1.7	0.4	0.4	0.1	0.4	0.4	0.0	0.5	0.4	0.1
Pair 5 (562, 661)	5:01	5:12	19	18	1.8	2	1.3	1.0	0.3	0.3	0.5	-0.1	0.6	1.4	-0.9
Pair 6 (553, 645)	4:36	4:38	18	17	1.6	2	0.9	0.5	0.3	0.4	0.5	-0.1	0.8	0.5	0.3

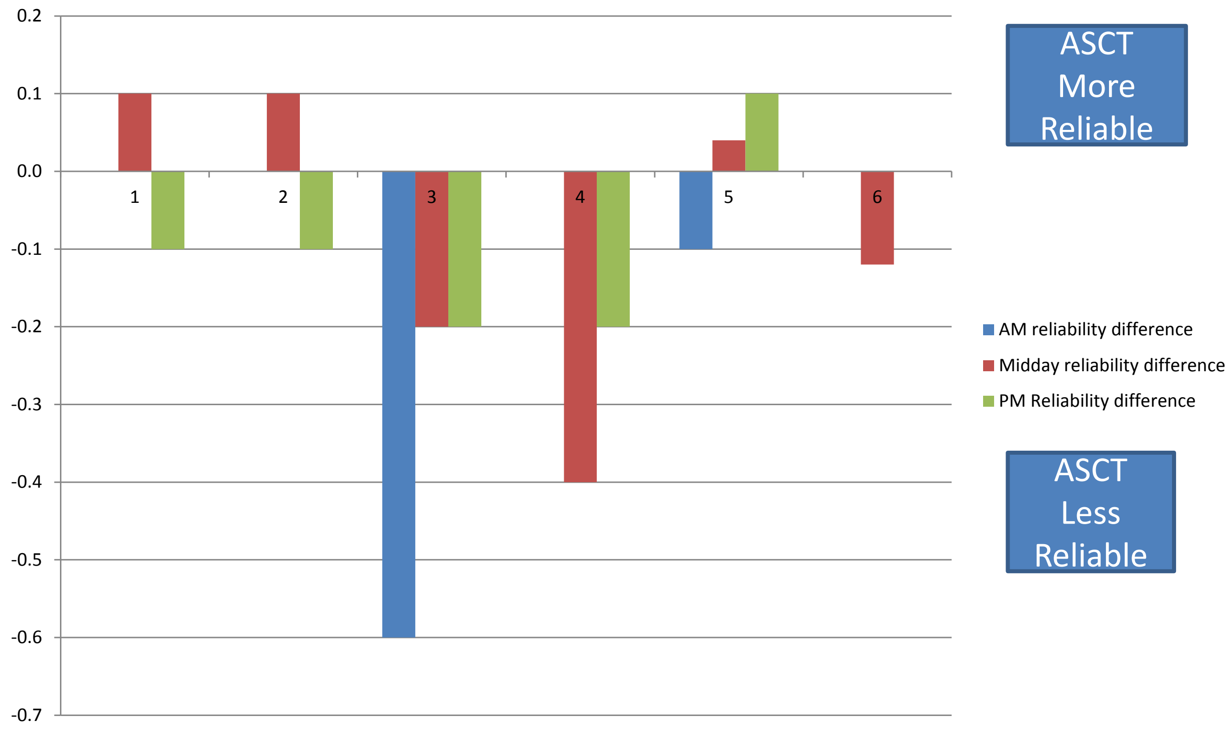


Figure 49. Bar graph. Buffer Time Differences for Each of the Six Bluetooth Pairs.
(Source: Kimley-Horn and Associates, Inc.)

Correlation of Travel Times to Route Volumes

Figures 50 and 51 illustrate the relationship between the travel time recorded on Power Road north and southbound (pairs "1" and "2", respectively) with the volume data collected at traffic counter "C". These graphs correlate to the findings obtained with the GPS probe trips: the ASCT favors southbound travel at the expense of northbound travel. The reliability findings shown above in Figure 23 do not, however, identify the same strong indication of southbound bias. One possible explanation for this difference is that the GPS probe continues the trip all the way through both terminus intersections, whereas the Bluetooth data do not include this portion of the trip since the vehicle is identified before traversing the intersection. This also explains the difference in the average travel times (GPS routes 7 and 8 as compared to Bluetooth pairs 1 and 2), which differ by roughly 1 minute.

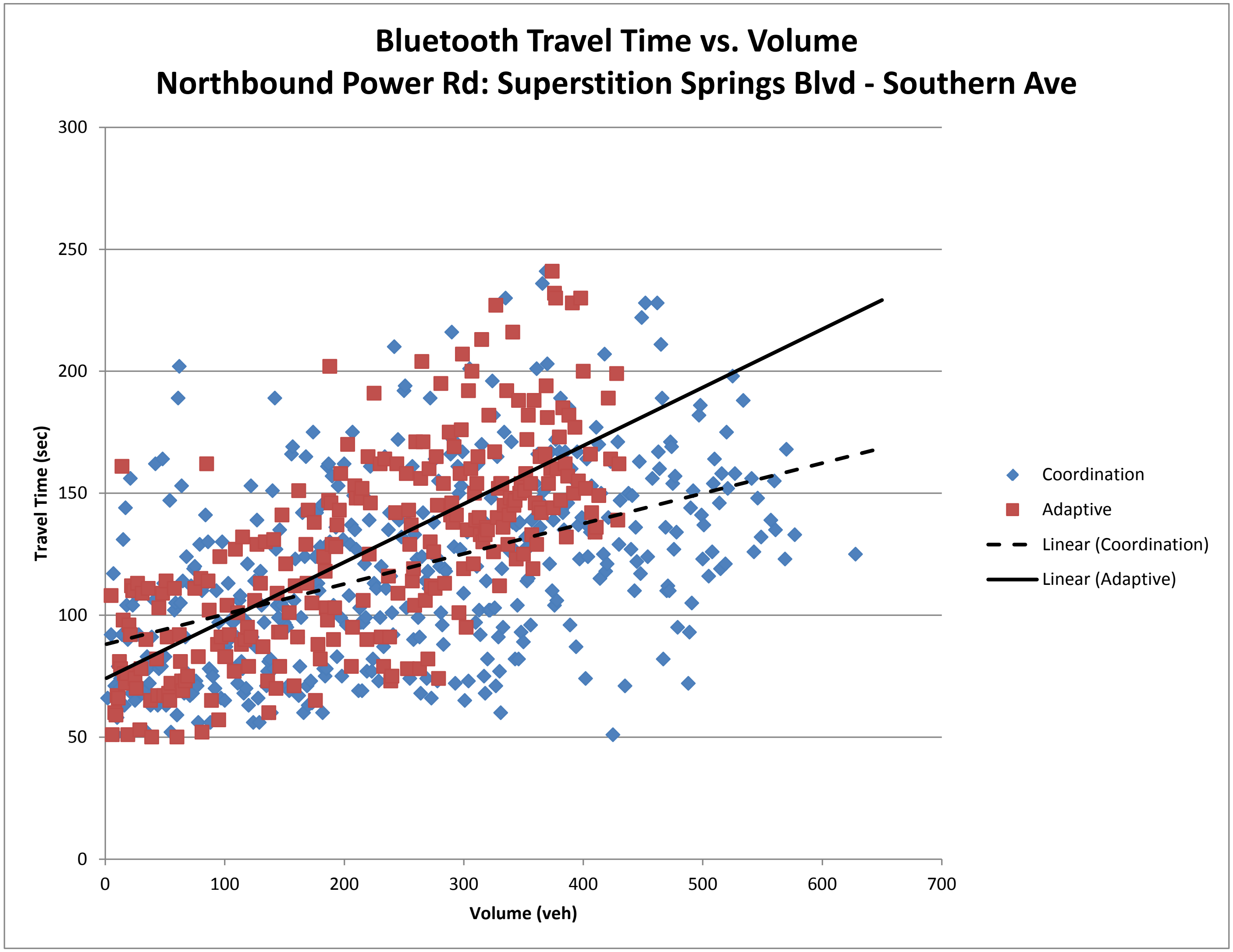


Figure 50. Line Graph. Comparison of Route Travel Times for Varying Volumes – Southbound.
(Source: Kimley-Horn and Associates, Inc.)

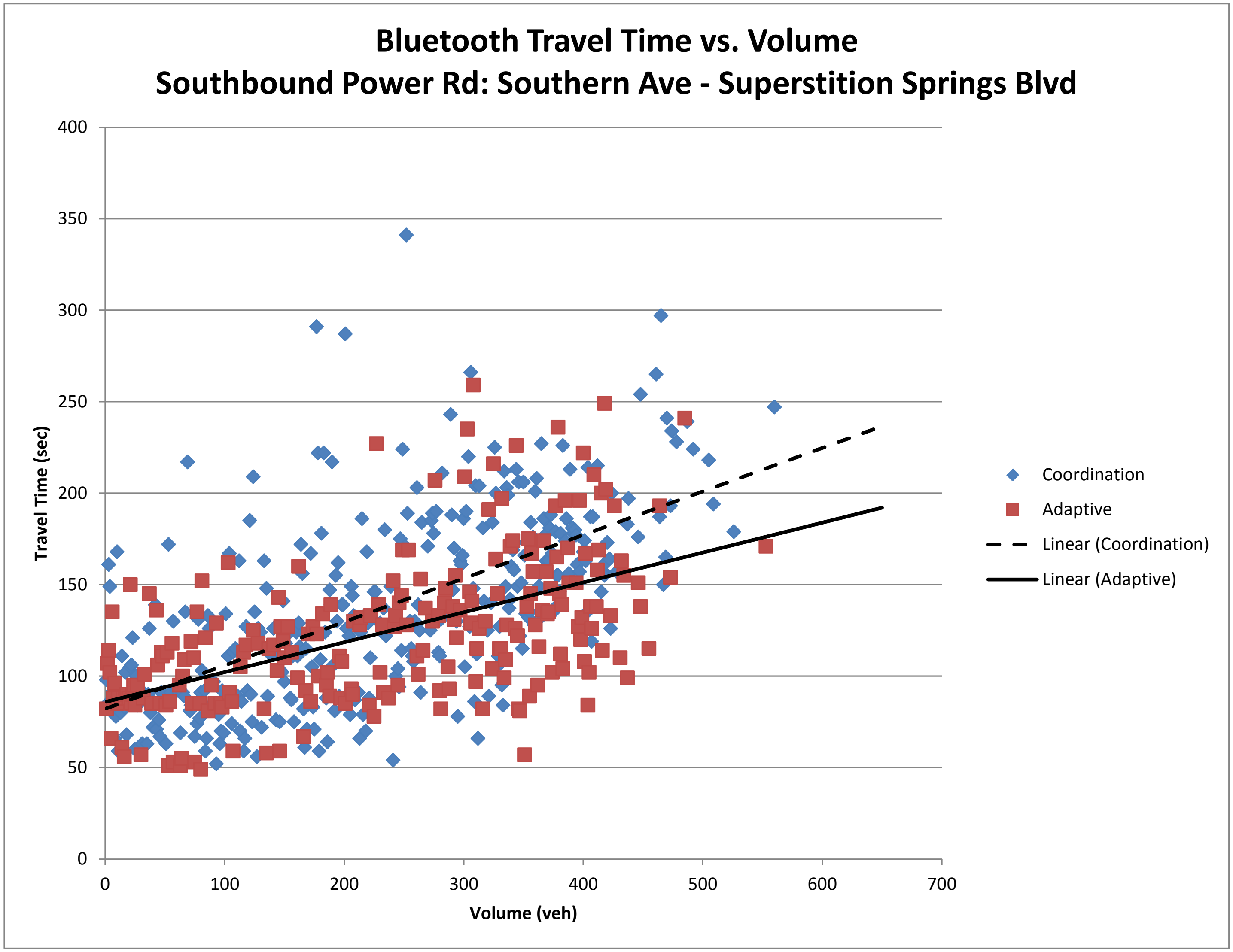


Figure 51. Line Graph. Comparison of Route Travel Times for Varying Route Volume – Southbound. (Source: Kimley-Horn and Associates, Inc.)

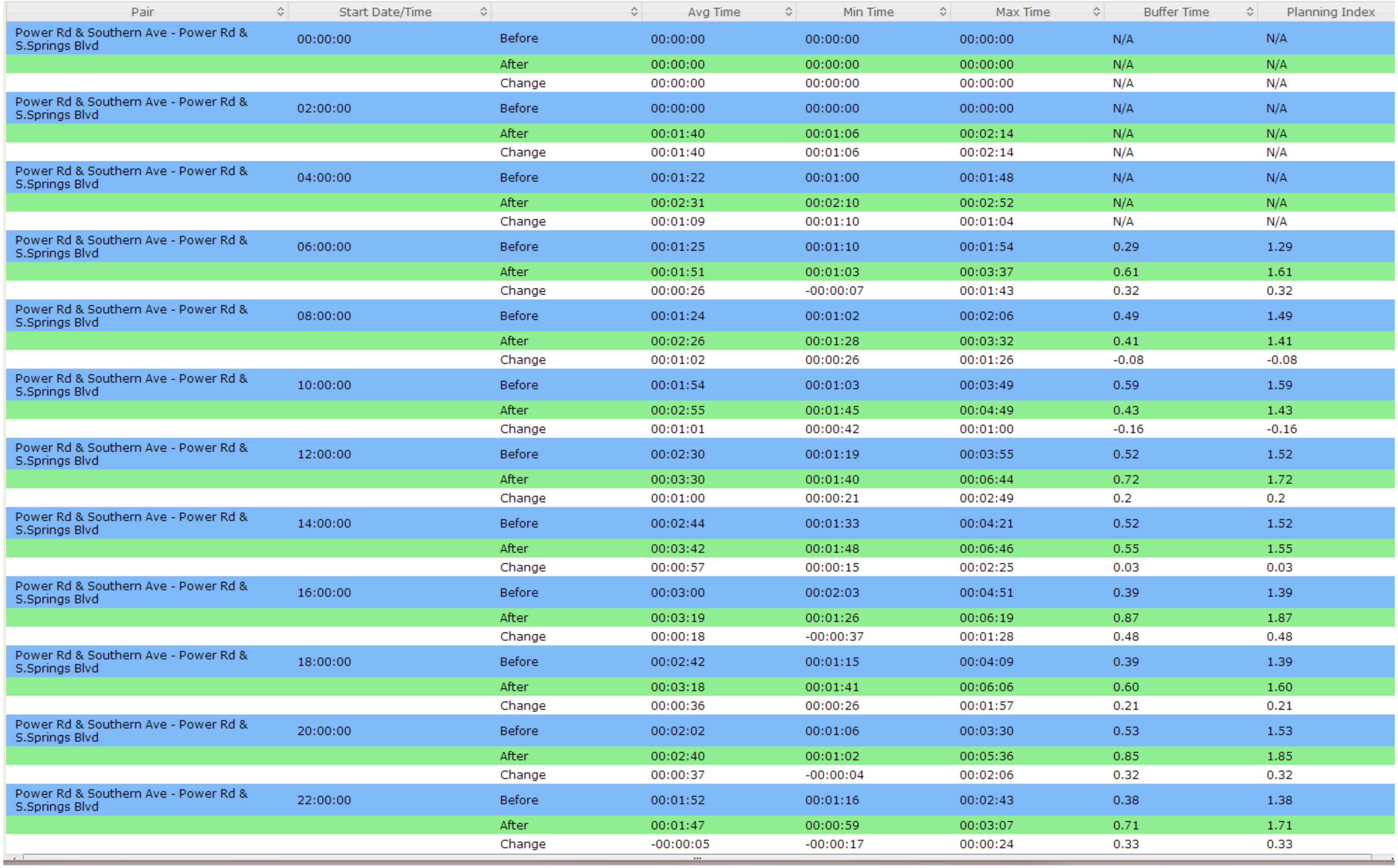
Summary of Bluetooth Travel Time Analysis

Table 14 summarizes the findings from comparison of coordinated operation and ASCT operation using the data from the Bluetooth travel routes. As indicated in the table, there is no strong indication that either system provides superior operation, or there a strong argument that a pipeline objective along Power Road is achieved. These findings also indicate that the underlying traffic patterns have not changed substantially since the ASCT was previously evaluated (at least the traffic patterns that would be identified by point-to-point travel times). The results of this data analysis are shown qualitatively in Table 13.

Table 14. Qualitative Comparison of Average Trip Time and Trip Reliability – Bluetooth Data

Bluetooth Pair	Average Travel Time	Buffer Time	Combined Result
1	ASCT better in mid-day and PM	No difference	ASCT better
2	Coordination better	No difference	Coordination better
3	ASCT better in mid-day and PM	Coordination more reliable	Mixed
4	Coordination better	Coordination more reliable	Coordination better
5	No difference	No difference	No difference
6	No difference	No difference	No difference

Endpoint to endpoint travel times are not particularly helpful for identifying where changes to signal timings can improve the operation, but they can be helpful in providing evidence that something is different. For example, Figure 52 illustrates the difference between the travel time on southbound Power Road on the day before Thanksgiving and the day after Thanksgiving (i.e., “Black Friday”). A few items are of note. First, the Bluetooth detectors identify enough travelers early in the morning to compute a travel time for those time periods on Black Friday, revealing a shift in departure times. Second, the buffer times and maximum travel times on Black Friday in some periods are significantly greater. If such changes can be identified close to real-time, signal control operations might be modified to improve the situation in the field.



Pair	Start Date/Time		Avg Time	Min Time	Max Time	Buffer Time	Planning Index
Power Rd & Southern Ave - Power Rd & S.Springs Blvd	00:00:00	Before	00:00:00	00:00:00	00:00:00	N/A	N/A
		After	00:00:00	00:00:00	00:00:00	N/A	N/A
		Change	00:00:00	00:00:00	00:00:00	N/A	N/A
Power Rd & Southern Ave - Power Rd & S.Springs Blvd	02:00:00	Before	00:00:00	00:00:00	00:00:00	N/A	N/A
		After	00:01:40	00:01:06	00:02:14	N/A	N/A
		Change	00:01:40	00:01:06	00:02:14	N/A	N/A
Power Rd & Southern Ave - Power Rd & S.Springs Blvd	04:00:00	Before	00:01:22	00:01:00	00:01:48	N/A	N/A
		After	00:02:31	00:02:10	00:02:52	N/A	N/A
		Change	00:01:09	00:01:10	00:01:04	N/A	N/A
Power Rd & Southern Ave - Power Rd & S.Springs Blvd	06:00:00	Before	00:01:25	00:01:10	00:01:54	0.29	1.29
		After	00:01:51	00:01:03	00:03:37	0.61	1.61
		Change	00:00:26	-00:00:07	00:01:43	0.32	0.32
Power Rd & Southern Ave - Power Rd & S.Springs Blvd	08:00:00	Before	00:01:24	00:01:02	00:02:06	0.49	1.49
		After	00:02:26	00:01:28	00:03:32	0.41	1.41
		Change	00:01:02	00:00:26	00:01:26	-0.08	-0.08
Power Rd & Southern Ave - Power Rd & S.Springs Blvd	10:00:00	Before	00:01:54	00:01:03	00:03:49	0.59	1.59
		After	00:02:55	00:01:45	00:04:49	0.43	1.43
		Change	00:01:01	00:00:42	00:01:00	-0.16	-0.16
Power Rd & Southern Ave - Power Rd & S.Springs Blvd	12:00:00	Before	00:02:30	00:01:19	00:03:55	0.52	1.52
		After	00:03:30	00:01:40	00:06:44	0.72	1.72
		Change	00:01:00	00:00:21	00:02:49	0.2	0.2
Power Rd & Southern Ave - Power Rd & S.Springs Blvd	14:00:00	Before	00:02:44	00:01:33	00:04:21	0.52	1.52
		After	00:03:42	00:01:48	00:06:46	0.55	1.55
		Change	00:00:57	00:00:15	00:02:25	0.03	0.03
Power Rd & Southern Ave - Power Rd & S.Springs Blvd	16:00:00	Before	00:03:00	00:02:03	00:04:51	0.39	1.39
		After	00:03:19	00:01:26	00:06:19	0.87	1.87
		Change	00:00:18	-00:00:37	00:01:28	0.48	0.48
Power Rd & Southern Ave - Power Rd & S.Springs Blvd	18:00:00	Before	00:02:42	00:01:15	00:04:09	0.39	1.39
		After	00:03:18	00:01:41	00:06:06	0.60	1.60
		Change	00:00:36	00:00:26	00:01:57	0.21	0.21
Power Rd & Southern Ave - Power Rd & S.Springs Blvd	20:00:00	Before	00:02:02	00:01:06	00:03:30	0.53	1.53
		After	00:02:40	00:01:02	00:05:36	0.85	1.85
		Change	00:00:37	-00:00:04	00:02:06	0.32	0.32
Power Rd & Southern Ave - Power Rd & S.Springs Blvd	22:00:00	Before	00:01:52	00:01:16	00:02:43	0.38	1.38
		After	00:01:47	00:00:59	00:03:07	0.71	1.71
		Change	-00:00:05	-00:00:17	00:00:24	0.33	0.33

Figure 52. Table. Comparison of Travel Times on Power Road Before and During Black Friday (Source: Kimley-Horn and Associates, Inc.)

FINDINGS USING HIGH RESOLUTION PHASE AND DETECTOR DATA

Complete phase timing data were available for all six intersections for two periods during the validation study:

- October 15th to October 31st.
- November 21st and December 3rd.

Note that only intersection “2” (Power & Southern) has advanced loops, so all percent arrivals on green and platoon ratio performance exhibits are based on the north and southbound directions at this intersection.

Summary Results for Time of Day Analysis of GOR Performance

Table 15 illustrates a summary of the comparison of average GOR and standard deviation of GOR for Superstition Springs & Southern (intersection “1”). Similar tables are presented for all of the other intersections in the system in Appendix B. The results are summarized across all the valid days of data collection for each hour of the day between 7 am and 10 pm (10 pm is shown as 22 in the table, representing military time). The columns indicate the following for each phase:

- The average GOR value for that hour of the day.
- The difference between the average GOR value for ASCT versus coordinated operation; negative values indicate that the coordinated average GOR is higher than the ASCT average.
- The difference between the standard deviation of the GOR value for ASCT versus coordinated operation; negative values indicate that the standard deviation for coordinated operation is larger than for ASCT operation.

Table 15. Difference between ASCT and Coordination for GOR by Time of Day – Southern and Superstition Springs (Weekdays)

Hour	2			5			6			8		
	Average of GOR	**GOR Difference**	**StdDev Diff**	**Average of GOR**	**GOR Difference**	**StdDev Diff**	**Average of GOR**	**GOR Difference**	**StdDev Diff**	**Average of GOR**	**GOR Difference**	**StdDev Diff**
7	0.08	0.03	0.03	0.08	-0.01	-0.01	0.09	0.02	0.02	0.54	-0.04	-0.04
8	0.08	0.02	0.02	0.11	-0.02	-0.02	0.10	0.01	0.01	0.49	-0.05	-0.05
9	0.08	0.01	0.01	0.13	-0.02	-0.02	0.12	0.00	0.00	0.49	-0.04	-0.04
10	0.10	0.01	0.01	0.15	-0.03	-0.03	0.14	0.00	0.00	0.53	-0.03	-0.03
11	0.11	0.01	0.01	0.24	-0.02	-0.02	0.17	0.01	0.01	0.55	-0.04	-0.04
12	0.12	0.01	0.01	0.24	-0.04	-0.04	0.17	0.00	0.00	0.56	-0.05	-0.05
13	0.13	0.01	0.01	0.24	0.00	0.00	0.17	0.01	0.01	0.57	-0.04	-0.04
14	0.12	0.01	0.01	0.20	-0.05	-0.05	0.16	-0.01	-0.01	0.57	-0.04	-0.04
15	0.12	0.01	0.01	0.19	-0.05	-0.05	0.16	0.01	0.01	0.60	-0.05	-0.05
16	0.11	0.01	0.01	0.22	-0.02	-0.02	0.17	0.01	0.01	0.63	-0.04	-0.04
17	0.11	0.01	0.01	0.21	0.02	0.02	0.16	0.02	0.02	0.60	-0.05	-0.05
18	0.09	0.01	0.01	0.14	0.00	0.00	0.12	0.01	0.01	0.56	-0.04	-0.04
19	0.07	0.00	0.00	0.08	-0.04	-0.04	0.09	0.00	0.00	0.55	-0.04	-0.04
20	0.06	0.00	0.00	0.05	-0.08	-0.08	0.08	-0.01	-0.01	0.54	-0.05	-0.05
21	0.06	0.01	0.01	0.04	-0.09	-0.09	0.06	-0.01	-0.01	0.50	-0.06	-0.06

Summary Results for Time of Day Analysis of Percent Arrivals on Green

Tables 16 and 17 summarize the comparison of average percent arrivals on green and standard deviation of percent arrivals for intersection 2 (Power & Southern,) which is the only intersection with advanced detection. The results are summarized across all the valid days of data collection for each hour of the day between 7 am and 10 pm (10 pm is shown as 22 in the table, representing military time). Phase 4 is southbound and Phase 8 is northbound. Some times of day have been excluded from the table because of anomalies in the data collection process. The columns indicate the following for each phase:

- The average percent arrivals value for that hour of the day.
- The difference between the average percent arrivals value for ASCT versus coordinated operation; negative values indicate that the coordinated average percent arrivals is higher than the ASCT average.
- The difference between the standard deviation of the percent arrivals value for ASCT versus coordinated operation; negative values indicate that the standard deviation for coordinated operation is larger than for ASCT operation.
- The average platoon ratio value for that hour of the day.
- The difference between the average platoon ratio value for ASCT versus coordinated operation; negative values indicate that the coordinated average platoon ratio is higher than the ASCT average.
- The difference between the standard deviation of the platoon ratio value for ASCT versus coordinated operation; negative values indicate that the standard deviation for coordinated operation is larger than for ASCT operation.

Table 16. Difference between ASCT and Coordination for Percent Arrivals on Green by Time of Day – Power and Southern (Weekdays)

	4						8					
Hour	**Average of % Arrivals on Green**	**Difference of % arrivals**	**StdDev Diff**	**Average of PlatoonRatio**	**Difference of PlatoonRatio**	**StdDev Diff PlatoonRatio**	**Average of % Arrivals on Green**	**Difference of % arrivals**	**StdDev Diff**	**Average of PlatoonRatio**	**Difference of PlatoonRatio**	**StdDev Diff PlatoonRatio**
7	0.36	-0.08	0.01	1.01	-0.20	0.11	0.51	0.02	0.00	1.37	0.13	0.00
8	0.40	-0.03	-0.02	1.10	-0.09	-0.02	0.49	0.07	0.04	1.29	0.17	0.10
9	0.37	-0.05	-0.03	1.07	-0.15	-0.08	0.19	-0.19	-0.08	0.54	-0.53	-0.23
10	0.40	-0.03	-0.03	1.18	-0.14	-0.12	0.19	-0.21	-0.10	0.55	-0.63	-0.32
11	0.44	-0.03	0.02	1.37	-0.09	0.16	0.23	-0.18	-0.07	0.70	-0.54	-0.17
12	0.40	-0.06	0.02	1.32	-0.14	0.10	0.22	-0.19	-0.08	0.75	-0.52	-0.05
13	0.39	-0.08	0.02	1.25	-0.24	0.07	0.25	-0.18	-0.07	0.78	-0.52	-0.15
14	0.41	-0.05	0.00	1.29	-0.21	-0.04	0.26	-0.15	-0.04	0.80	0.55	-17.32
16	0.41	0.03	-0.01	1.29	0.13	-0.02	0.21	-0.21	-0.09	0.65	-0.60	-0.24
19	0.34	-0.01	-0.02	0.97	-0.12	-0.15	0.29	-0.15	-0.03	0.74	-0.41	-0.15
20	0.37	0.03	0.02	1.02	0.06	0.04	0.41	-0.02	0.04	1.00	-0.06	0.11
21	0.41	0.02	0.00	1.00	-0.04	-0.12	0.52	0.05	0.05	1.15	0.05	0.20
22	0.40	0.01	0.01	2.00	0.76	9.76	0.43	-0.03	0.03	-0.27	-1.13	10.81

Table 17. Difference between ASCT and Coordination for Percent Arrivals on Green by Time of Day – Power and Southern (Weekends)

	4						8					
Hour	Average of % Arrivals on Green	Difference of % arrivals	StdDev Diff	Average of PlatoonRatio	Difference of PlatoonRatio	StdDev Diff PlatoonRatio	Average of % Arrivals on Green	Difference of % arrivals	StdDev Diff	Average of PlatoonRatio	Difference of PlatoonRatio	StdDev Diff PlatoonRatio
7	0.40	0.11	0.00	0.97	0.05	-0.19	0.32	0.00	0.00	0.71	-0.21	-0.49
8	0.41	0.12	0.00	1.04	0.12	-0.10	0.29	-0.07	-0.03	0.69	-0.40	-0.30
9	0.36	0.05	0.02	1.07	-1.50	-16.73	0.22	-0.10	-0.05	0.60	-0.41	-0.25
10	0.38	0.00	0.02	1.12	-0.10	0.01	0.23	-0.14	-0.05	0.63	-0.52	-0.26
11	0.43	0.01	0.05	1.41	0.07	0.27	0.22	-0.19	-0.07	0.69	-0.62	-0.23
12	0.35	-0.08	0.02	1.32	-0.04	0.99	0.21	-0.18	-0.08	0.79	-0.42	0.25
13	0.35	-0.07	0.04	1.20	-0.14	0.15	0.24	-0.16	-0.08	0.81	-0.45	-0.21
14	0.34	-0.07	0.02	1.15	-0.18	0.07	0.28	-0.15	-0.06	0.92	-0.39	-0.21
16	0.34	-0.03	0.00	1.14	-0.08	0.07	0.24	-0.13	-0.05	0.79	-0.40	-0.12
19	0.39	0.10	0.00	1.04	0.03	-0.23	0.38	0.04	-0.02	0.94	-0.04	-0.14
20	0.39	0.09	0.02	0.99	-0.08	-0.20	0.54	0.14	-0.01	1.21	0.12	-0.41
21	0.44	0.16	0.01	1.04	0.08	-0.24	0.57	0.23	0.00	1.28	0.39	-0.03
22	0.46	0.10	0.03	2.68	-0.38	-5.30	0.54	0.12	0.03	0.37	-0.36	3.97

As indicated in other parts of this report, the data on percent arrivals on green does not indicate a strong conclusion that either type of operation provides a pipeline type operation on Power Road, particularly at this critical intersection. Both the percent arrivals on green and platoon ratio MOEs indicate that coordinated operation provides marginally better performance, but the coordinated operation also has a higher standard of deviation, indicating less reliable performance than ASCT for both weekday and weekend traffic conditions.

Examples of More Detailed Analysis of High-Resolution Phase Timing Data

Figure 53 illustrates how the average GOR values change over a typical Saturday at intersection 2 when ASCT is in operation. A criterion one might use to determine if the ASCT is providing equity access is that the GOR values on each phase are approximately the same. This objective is clearly not the only objective being considered by the ASCT, since in particular phase 2 (eastbound through traffic) has a much lower GOR value than the other phases. The volumes on this phase are noticeably lower than the other through phases 4, 6, and 8. This is explained, possibly, by two facts. First, the ASCT is not allowed to modify the sequence in this deployment, so with leading left turns, phase 2 must terminate with phase 6 (which has higher volume), dragging phase 2 out longer than necessary due to barrier crossing requirements. Second, the movement experiences frequent pedestrian activity (more so on a Saturday in the middle of the day), which might extend the duration of phases 2 and 6 longer than necessary to serve vehicle demand.

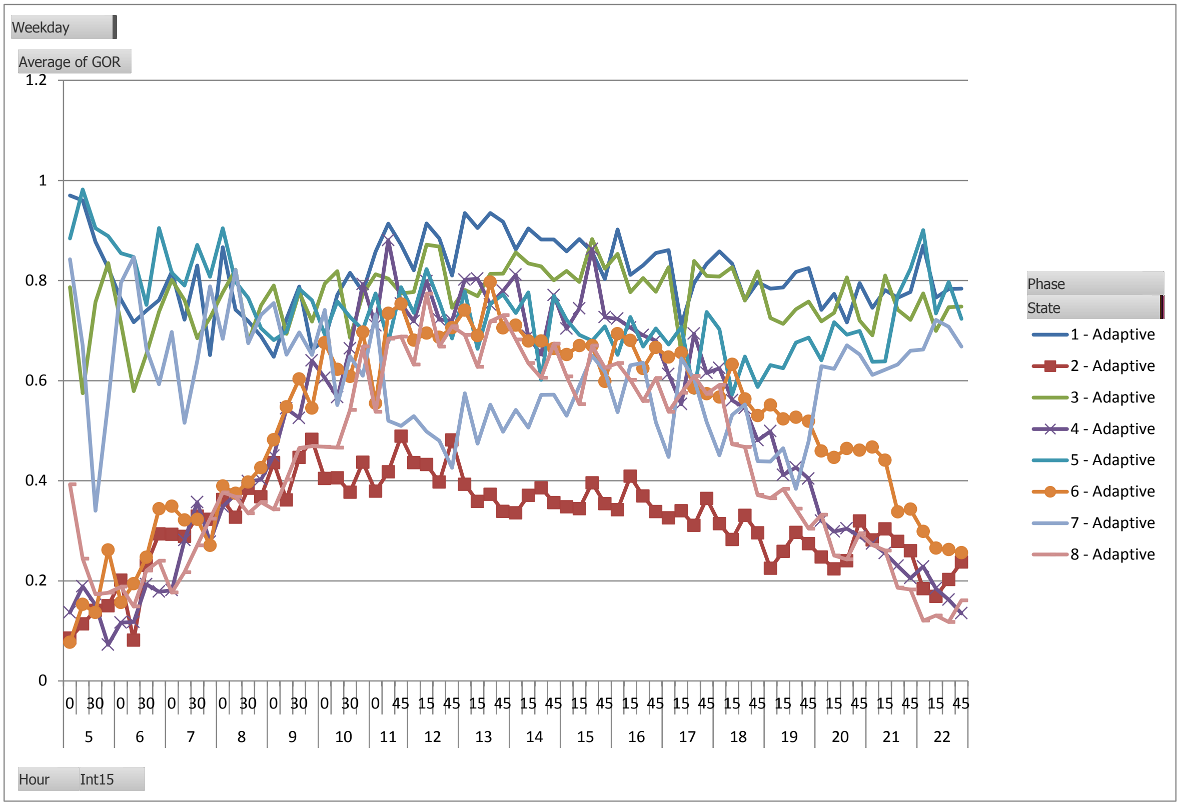


Figure 53. Line Graph. Average GOR Over Time for ASCT Operation at Power and Southern on Saturdays
(Source: Kimley-Horn and Associates, Inc.)

Contrast Figure 53 with Figure 54 below illustrating the average GOR values on Saturdays resulting from coordinated operation. The GOR values for left turn phases (1, 3, 5, 7) are noticeably higher under coordination. The ASCT has increased the cycle time and slightly decreased the splits for coordinated phases to drive the GOR values closer to a more reasonable value of ~0.8. This is what it is designed to do; thus, this artifact illustrates the ability of the ASCT to meet its operational objective of providing equity access.

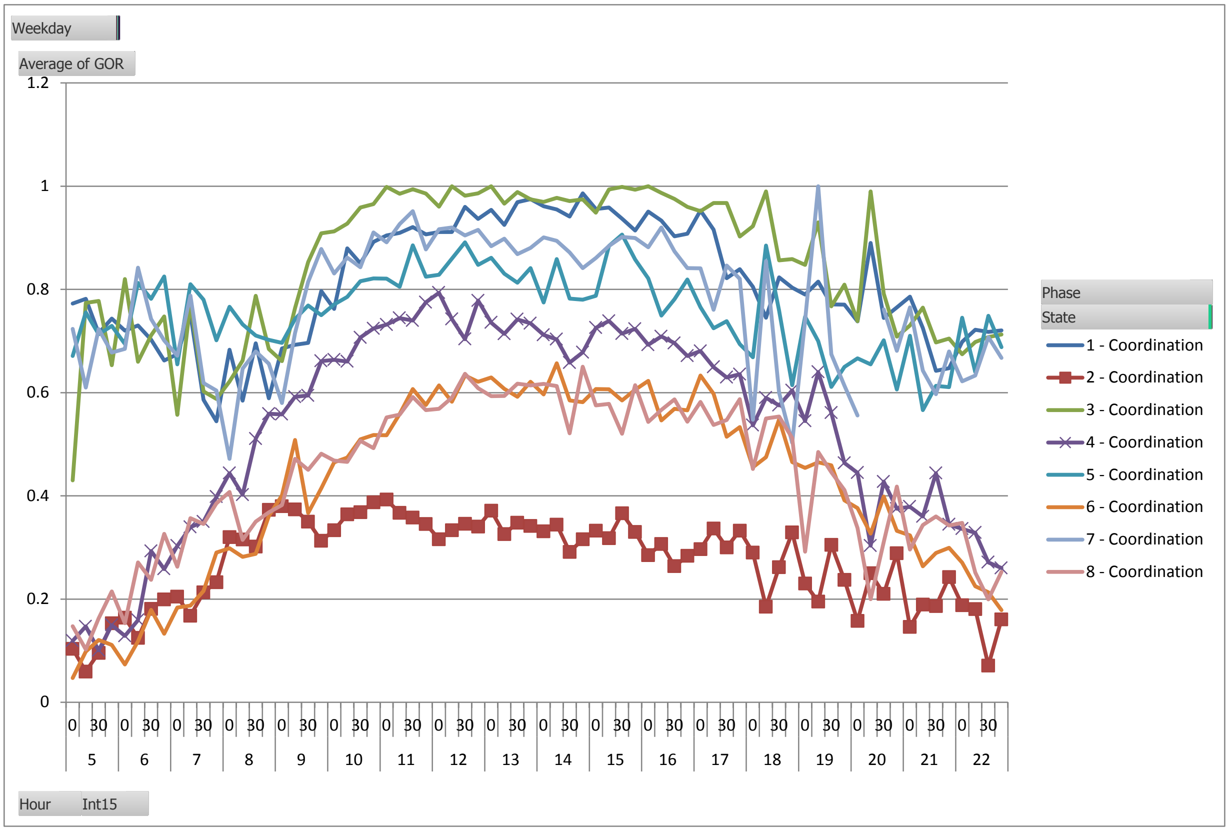


Figure 54. Line Graph. Average GOR Values Over Time for Coordinated Operation at Power and Southern on Saturdays
(Source: Kimley-Horn and Associates, Inc.)

Figure 55 further corroborates other findings that indicate that the ASCT focuses on northbound traffic at the expense of southbound traffic flows. While neither type of operation produces particularly impressive progression performance in the heaviest hours of the peak period, the ASCT reduces southbound progression performance even further to maintain equity access for other phases after 9 am. In and of itself, this appears to be a poor decision, but other modifications being made at adjacent locations must be considered as well.

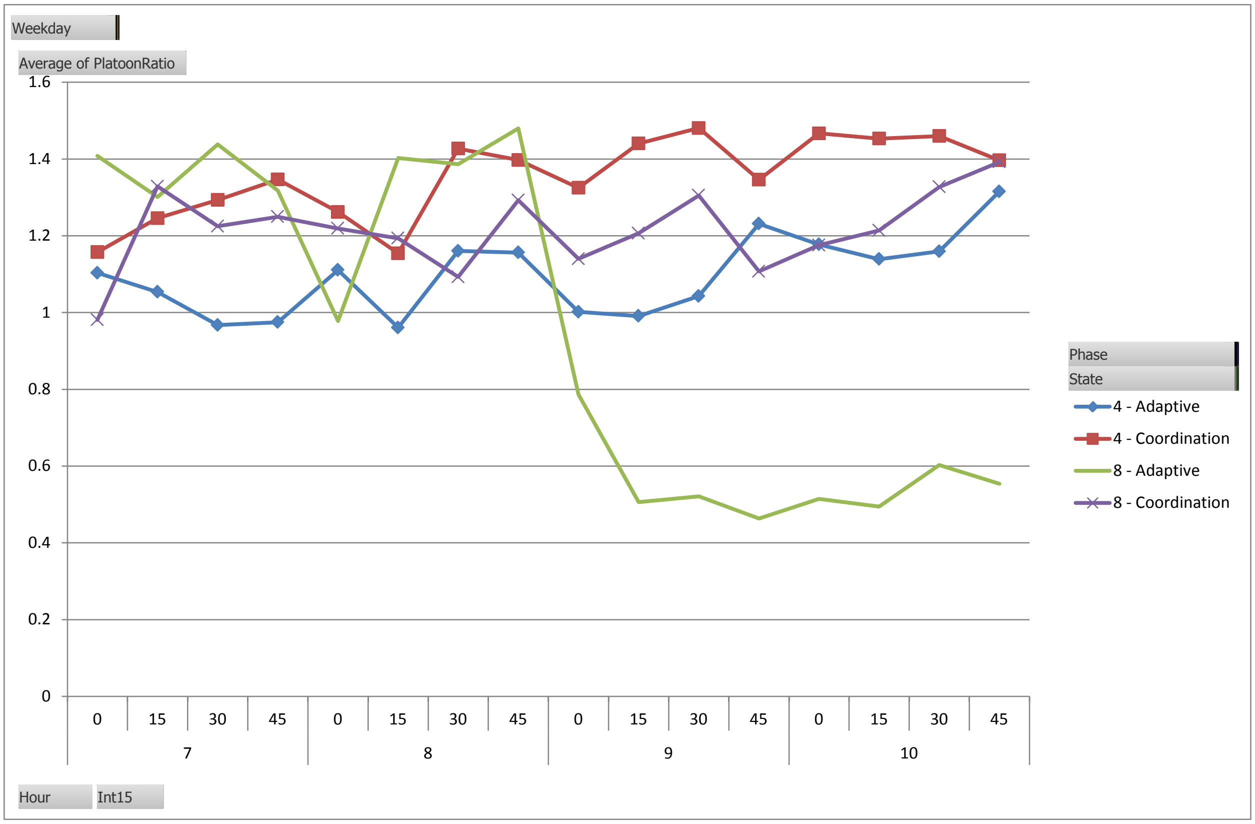


Figure 55. Line Graph. Comparison of Average Platoon Ratio 7-10 AM on Representative Weekdays – North and Southbound at Power and Southern
(Source: Kimley-Horn and Associates, Inc.)

Example of Pitfalls in Reporting and Consideration of Percent Improvement Data

While GOR and percent arrivals on green provide meaningful measures to compare signal operations, one must still be careful in using these measures. Figure 56 compares the GOR values between ASCT and coordinated operation for phases at intersection 1 (Southern and Superstition Springs, the intersection with the lowest total flows). The y-axis displays the percent difference between the GOR value for ASCT and coordination on Sundays during the study period. Values greater than zero indicate higher GOR for ASCT. Except for GORs that trend at 1.0, higher GOR generally indicates "snappier" operation as the signal control terminates the green phase earlier after vehicle demand has dissipated. At first glance, the improvements in the early morning and late evening indicate superior performance for the ASCT, with at times greater than 60% higher GOR.

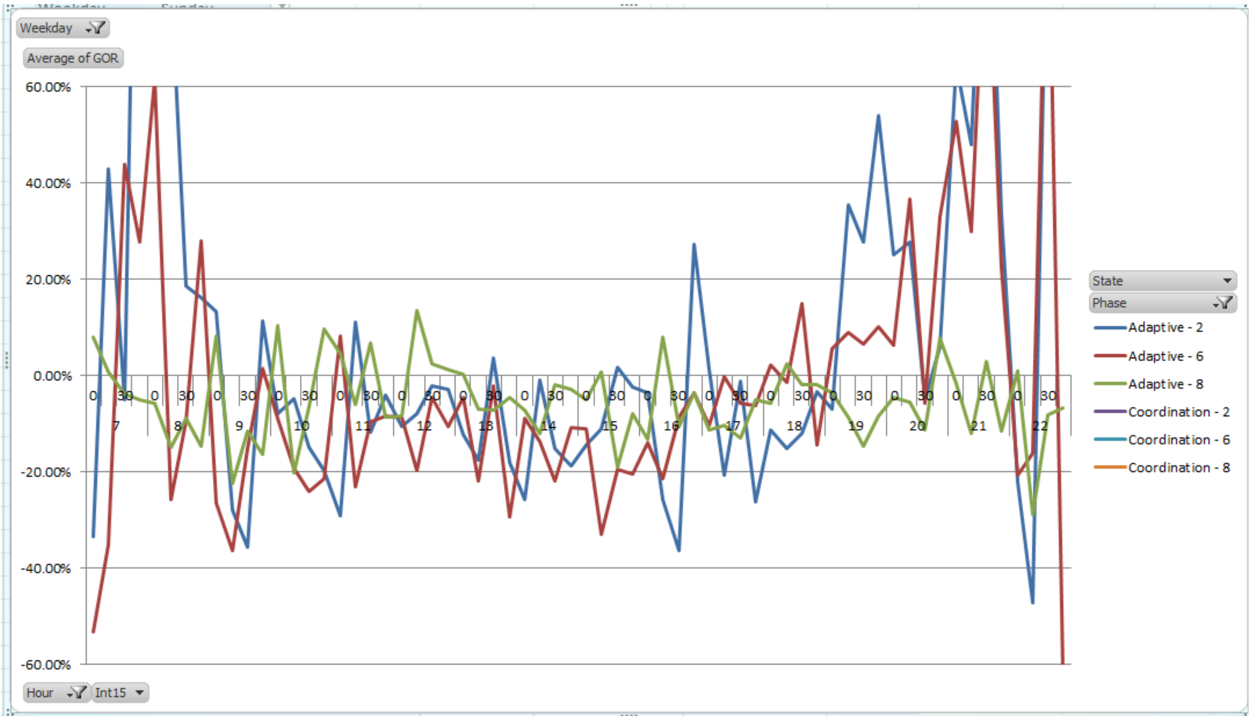


Figure 56. Line Graph. Percent Differences in GOR between Adaptive and Coordination on Sundays at Intersection 1
(Source: Kimley-Horn and Associates, Inc.)

Figure 57 illustrates the average GOR values for phases at intersection 1 on Sundays. As shown, the GOR values are very low, essentially indicating that one or two vehicles are arriving to be served and the system is timing the minimum green. This indicates that at very low volumes, the ASCT is better than the coordinated operation at terminating the phase early and moving on to the next phase with demand. This is certainly a reasonable benefit of ASCT application for individual drivers, but in aggregate the benefits are negligible. Percentages should always be taken with a grain of salt.

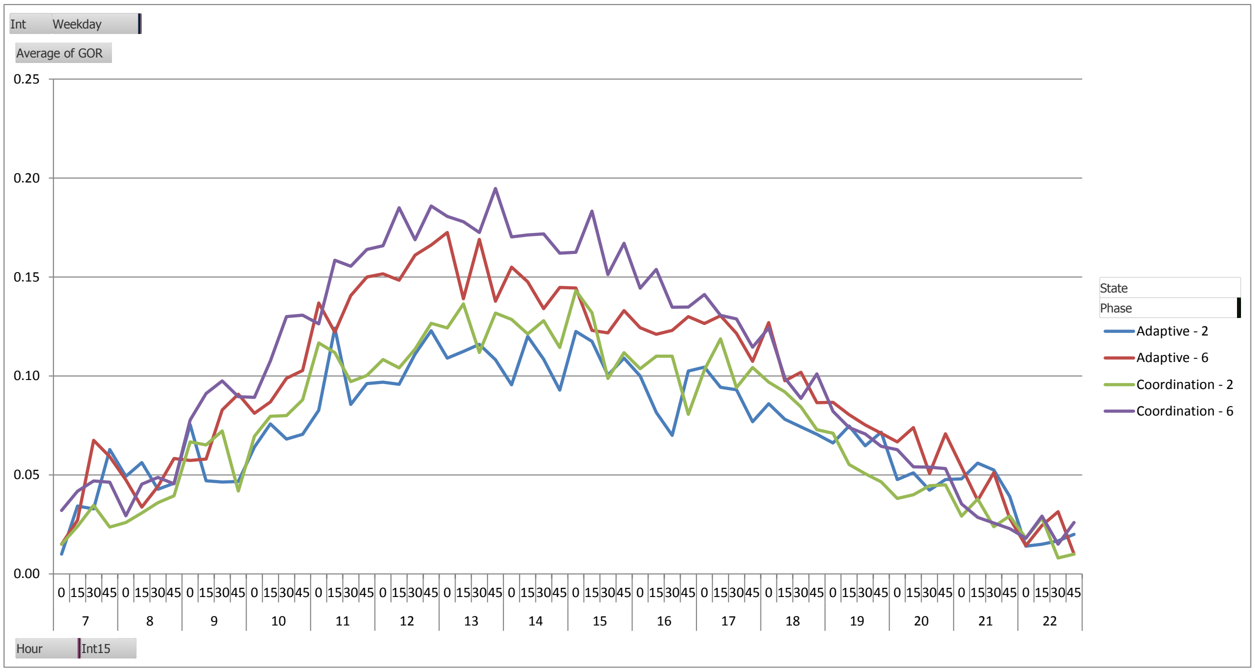


Figure 57. Line Graph. Average GOR Values on Sundays at Intersection 1
(Source: Kimley-Horn and Associates, Inc.)

VOLUME COUNTER FINDINGS FOR THROUGHPUT ESTIMATION

Volume counters were installed for measurement of flow at key entry and exit points to the major arterial, Power Road, from the east, west, and south. These measurement points were used to determine that the traffic flows were approximately the same during ASCT and coordinated operation, to match travel times with flows, and to measure throughput. The ability of a system to manage queues can be estimated from the total throughput at a certain point. Comparison of day of week and time of day flows did not show any significant differences in the distribution of peak periods or other differences between times when ASCT and coordination were in operation. This was not surprising, as an ON/OFF study was conducted over a compressed period of time (two months) with an approximately equal number of ON and OFF days and distribution of those days across days of the week.

Throughput performance was analyzed by selecting a given count detector and identifying a target volume. The analysis algorithm calculates, to the nearest minute, the time it takes to accumulate the target volume from the starting time. Starting times are tabulated in 15 minute increments. Figure 58 illustrates a comparison of the processing time for ASCT on the y-axis and coordination operation on the x-axis for the eight dates when GPS travel time data runs were collected. The points shown begin at 6:00 am through 5:45 pm. The target volume was 3000 vehicles for this location. Other locations used different target volumes as shown in each graph in Appendix C.

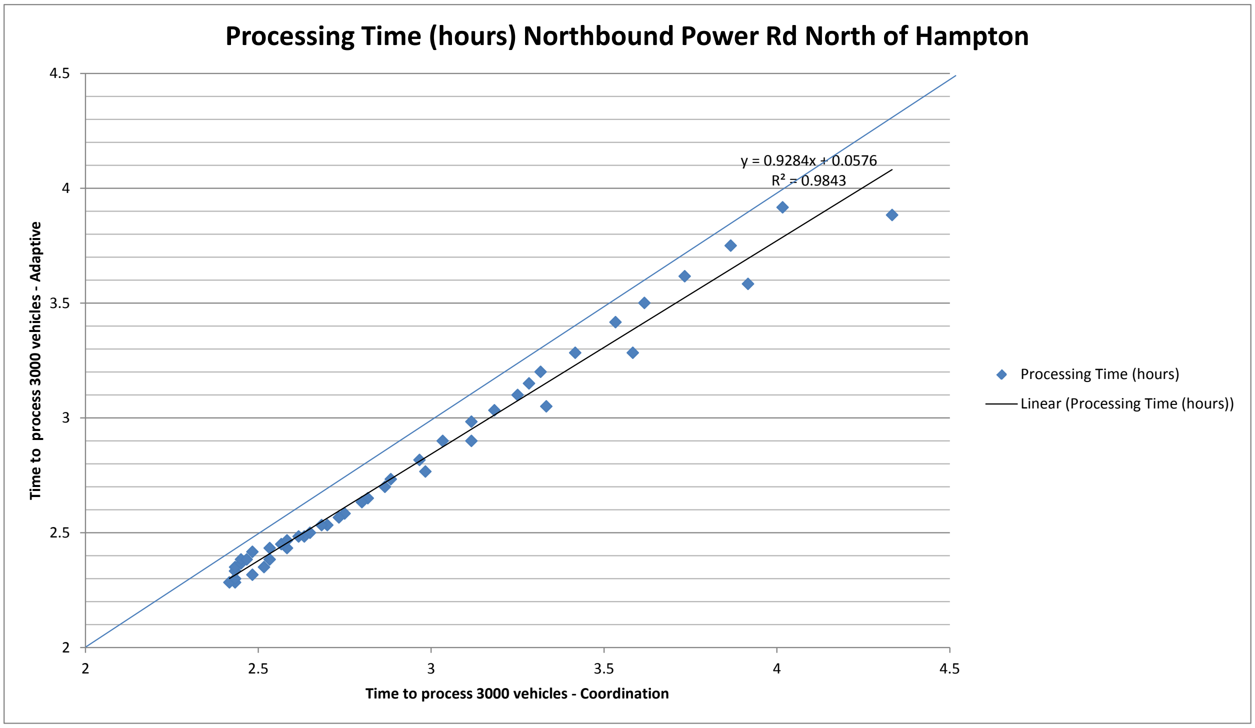


Figure 58. Line Graph. Throughput Performance for ASCT versus Coordination – Volume Counter "C", Northbound
(Source: Kimley-Horn and Associates, Inc.)

As shown in the figure, ASCT shows a noticeable performance benefit for every starting time. The effect also appears to be amplified at later start times that also correspond to lower volumes. The ASCT achieves the target volume sooner than coordinated operation, indicating that it is more efficient at processing low volumes since at this time it operates more as if it is in "free" mode, reserving less time for the coordinated band. Since this counter is on the main arterial (Power Road), there is a strong indication that either (a) perhaps the system would be more efficiently operated in "free" mode earlier in the evening, or (b) the offset at Power Road is not set for northbound travel. This indication corroborates other findings such as the percent arrivals on green and platoon ratio metrics from the controller data that indicate poor coordination performance at Power and Southern.

Appendix E presents graphs of the throughput performance for the other traffic counters used in the study. Four show minor but measurable benefits for ASCT operation in throughput performance, and the other three indicate no significant difference in the two types of operation.

APPENDIX E. FINDINGS FOR VALIDATION OF ASCT OPERATIONAL OBJECTIVES

The previous chapter presented specific results for the various MOEs that were tested in this project. As presented in the previous chapter, the analysis of various results indicates that the ASCT and coordination operation have very similar characteristics for this particular deployment location. Neither operation was found to be uniformly more effective than the other at performance on the collected MOEs when assessed at aggregate levels typical of most validation efforts. However, the goal of validation is not to generate a specific percentage or level of improvement; the goal of validation is to determine that the strategy or tactics meets the operational objectives of the agency in implementing the strategy. If the existing strategy is acceptable and the new strategy cannot improve upon it, this is not a "failure" of the new strategy; it most likely means that the existing operation is largely acceptable. On the other hand, it can mean that neither operation is performing acceptable for the agency objective. Some analysis of specific findings is presented here to illustrate some of the challenges in interpretation. Again, our goal in this project is not to evaluate the specific system in Mesa, Arizona but rather to demonstrate how each MOE can be used to validate a common agency objective for deploying ASCT.

FINDINGS FOR THE ACCESS EQUITY OBJECTIVE

Both types of operation meet the agency objective to provide access equity at each of the intersections as measured by qualitative review of the GOR values. At most intersections during most periods of the day, the maximum values of average GOR were lower than coordinated operation, indicating that the ASCT modifies the split timings more often to reduce the possibility of phase failures. This indicates that the ASCT is indeed reacting to the changes in the traffic flows, which is not possible with coordination timings with fixed split values, although in most cases the gap-out logic of the coordinated operation still provides acceptable performance.

In some cases, GORs were found to not be as balanced as possible during ASCT operation because of the influences of other system users, primarily pedestrians. For example, the crossing phases (2 and 6) at the critical intersection (Power & Southern) were extended significantly past the time needed for crossing traffic in order to time the pedestrian clearance. This results in significant queues on the coordination phases (4 and 8) and lower GOR values for the crossing phases (2 and 6) due to the extended phase durations. It seemed plausible that the ASCT should have increased the cycle time to lower the degree of saturation on the coordinated phases and bring the levels of service of all phases more in balance (in the process improving progression for the north and south (4 and 8)), but it did not. Why not? This is a very difficult question to answer since there are a number of components to the decision making process in any ASCT that are unobservable.

Assuming that we are not observing issues that are the result of programming errors or logical faults (in this case, the ASCT is quite mature and unlikely to include basic logical or algorithmic errors), it is more likely that the un-common-sense outcomes (a) are due to the complexity of the decision making process, which cannot easily be explained in the documentation, (b) may be too complicated for simple “if-then” descriptions, or (c) are influenced by thresholds, parameters, and configuration settings that we have not considered.

In this deployment, agency staff were not accustomed to “playing” with the parameters and setup of the system (most of the staff involved in the procurement and installation of the ASCT system have since taken other positions with other agencies or retired) and were certainly hesitant to start modifying settings of the system when they viewed the operation as largely acceptable. Since the project was ongoing, any tweaking of the operation would have created a third regime to be evaluated (coordination, original ASCT settings, and modified ASCT settings). The good news, however, is that if the agency decides to study the before and after differences of parameter changes, they can relatively quickly and inexpensively assess those modifications with the tools and methodology developed in this project from the data collected and uploaded from the controllers. GOR values identify acceptability of phase durations to meet traffic demand. As an agency starts the process of optimizing a system to meet certain performance objectives, the changes are easily revealed by observing the GOR values obtained from the high-resolution signal timing data without extensive additional deployment of observers in the field. Consistently high GORs can easily indicate the need for more split time on a phase. Consistently low GORs can easily indicate the need for less split time for a phase. Care should be taken in the case of low GOR values since there are can be other influences that result in low GOR such as the need to cross a barrier with a phase in another ring or because of pedestrian actuations.

FINDINGS FOR THE PIPELINE OBJECTIVE

While both actuated-coordinated operation and the ASCT perform adequately to provide access equity, the pipeline objective on the main north-south arterial in the system could not be qualitatively validated for either type of operation. With over 2.5 stops/mile on average in both directions of travel on a route that is less than a mile in length, the pipeline objective is clearly not being achieved. In this system, there is a freeway interchange in the mix, which creates some additional complexity due to the heavy off ramp flows at certain times of day. Even so, both types of operation generally had poor progression performance at the critical intersection for both north and southbound travel as revealed by all of the pipeline-related MOEs. Arrivals on green, stops per mile, platoon ratio, and link and route travel times were shown to all be acceptable MOEs that can validate that an operational strategy meets or does not meet a pipeline objective. The vehicle re-identification method is weakest at pinpointing specific areas for improvement but the 24x7 coverage can provide a wealth of observations for analysis. Probe travel time runs provide the richest set of details about specific characteristics of the route performance, but are expensive to collect in order to generate a reasonable performance sample. Percent arrivals on green and platoon ratio measures require advance detection on approaches to intersections and provide link by link view of progression performance. Methods are still needed to combine these link MOEs together to generate route MOEs.

FINDINGS FOR THE TRAVEL TIME RELIABILITY OBJECTIVE

Significant differences in reliability of travel times for several routes were identified using both GPS probe runs and Bluetooth travel time detectors. Coordinated operation was shown to have lower buffer times and thus higher reliability for several of the routes. The northbound route on

Power Road with ASCT was found to be more reliable than coordinated operation, which correlates with other findings that the ASCT favors northbound travel at the expense of southbound traffic. While it was theorized that we might find that the ASCT was able to improve reliability even when the average travel time might be slightly worse than coordinated operation, this was not the case. This reinforces the case for traditional traffic engineering approaches in situations with steady, predictable traffic flows, because appropriately configured coordinated operation can be superior to, if not as least as effective as, ASCT systems with their fluctuating natures. Buffer time was shown to be an acceptable metric for validating that an operational strategy can satisfy a reliability performance objective. Buffer time is easiest to compute when there are many observations in a time period, such as with vehicle re-identification systems. When computing reliability metrics for travel times from GPS probe data, the main challenge is collection of enough trips in a time period for capturing a reasonable estimate of the true buffer time. Methods based on Bayesian statistics are likely necessary (Feng, et al, 2012) when the number of probe trips are very low.

FINDINGS FOR THE THROUGHPUT OBJECTIVE

Using the data from the traffic volume counters, the ASCT objective was shown to induce measurable improvements to the throughput performance at several locations. These differences cannot be explained by randomness in the vehicle flows or systemic differences in the ON and OFF data sets, since the measurements were averaged over many days of data collection and using the same days of the week in both ON and OFF conditions. With respect to several of the point locations, at least, this supports the theory that ASCT can increase throughput by subtly modifying the splits of a given phase, cycle by cycle, thus reducing the number of phase failures.

In at least one location, the improvement was manifested during all times of day, but particularly when the traffic flows transitioned from PM peak to post-peak conditions, the ASCT operation tended to process vehicles more quickly to the desired target volume than coordinated operation. This corroborates the often conjectured ability of ASCT to be able to curb the peak period performance condition sooner (which can typically be quite poor, with standing queues and significant congestion) than coordinated operation. Since traditional signal operations do not vary the splits and other parameters with respect to traffic demands, the small changes made by ASCT can have a positive effect in improving throughput. Perhaps this suggests that some coordinated systems should be transitioned from a pipeline objective (coordination) to an access equity objective (free) sooner than typically scheduled in most fixed-parameter operations; it is more indicative, however, of the capability of ASCT to balance both objectives (access equity and pipeline) together during the shoulder periods, since both flows (left turns from the side-streets and through flows from the main line) contribute to the total throughput at the outbound measurement locations.

Measurement of total flow across a point location over a given time period was shown to be an acceptable MOE for determining that a signal timing strategy meets the objective of improving throughput. Care must be taken to average the results over many days and similar days of the week to avoid making erroneous conclusions that are due only to fluctuations in traffic demand or differences in traffic patterns.

QUALITATIVE VERSUS QUANTITATIVE VALIDATION

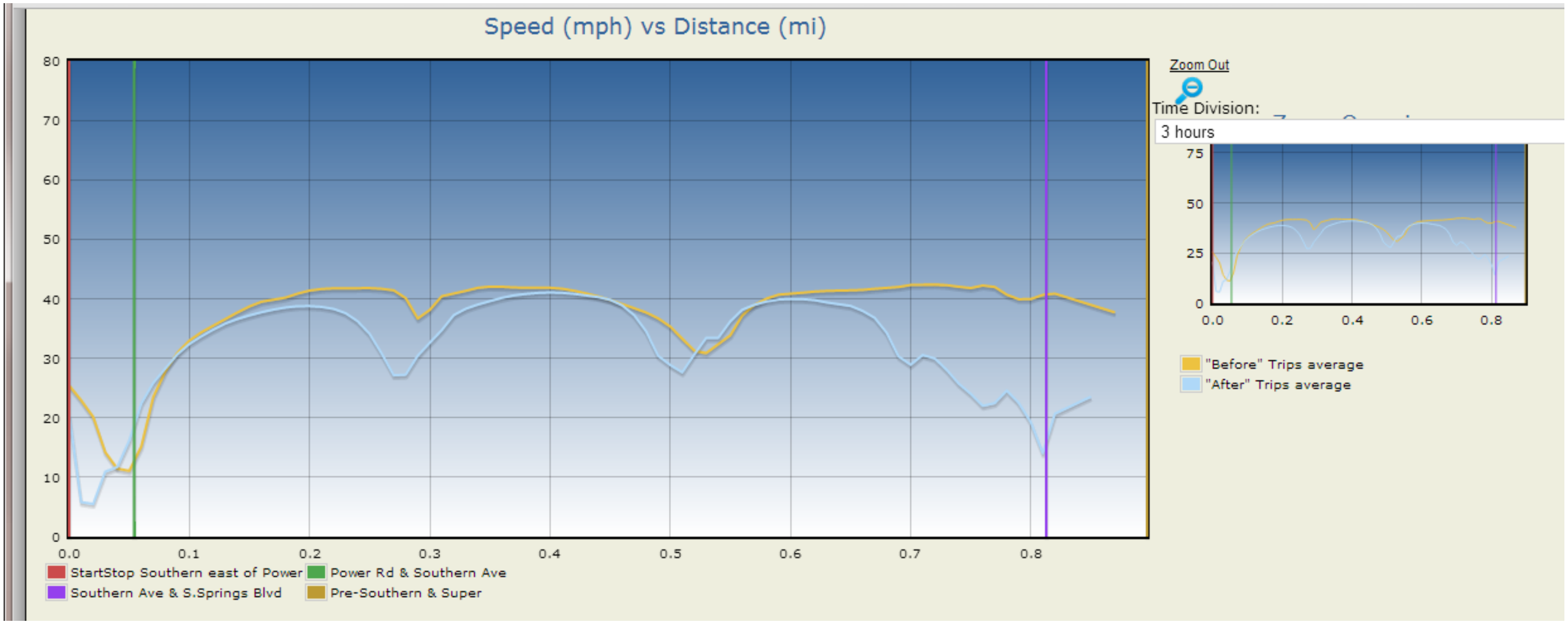
We have been careful to use the words “qualitative” validation in the preceding sections on analysis of the findings, because there is no existing quantitative specification for what GOR values or percent arrivals on green at an intersection or along a route constitute acceptable performance for a given objective. These criteria need additional research and development, perhaps starting from the concepts established from the HCM criteria of average delay for a phase or average speed on a link. In particular, standards need to be established for evaluating performance without the need to compare a certain type of operation with what was being done before. Comparing ASCT performance with existing performance is the largest contributor to uncertainty of benefits because of the variation in baseline performance across jurisdictions.

HCM criteria measure the level of demand as much the quality of service. A particular type of operation has little chance of obtaining an “A” score if the level of demand is simply too large. Similarly, an objective to “manage queues” may mean providing a certain level of throughput on a particular direction of travel. But to what extent can such an objective be considered validated without comparing the operation to some other type of control? Because there are no criteria for the speed with which standing queues should be dissipated once they begin to grow, we are left to reason that if a certain type of operation improves upon the previous operation, it is superior, and if it does not, it was a waste of funds, time, and effort.

As has been shown in this particular test, there are operational regimes in which ASCT is simply not able to improve significantly upon traditional coordinated (or “free”, for that matter) operation, *when the traffic flows are predictable and stable and the signal timing parameters are set appropriately*. This is not a strike against ASCT, but rather a strong endorsement of the fact that traffic engineering has evolved to address the cumulative feature set of actuated-coordinated operation that functions well under minor flow fluctuations. When the fluctuations exceed the bounds of actuated-coordinated assumptions, *and there are valid trade-offs that can be made*, there is no doubt that ASCT can improve system operation. How these performance improvements can be quantitatively validated is still elusive. In many past studies, such situations are simply not measured (indicating that ASCT systems have “no impact”) and in others those situations are easily identified or induced (indicating that ASCT systems have “enormous impact”). What is needed are ways to quantitatively demonstrate that ASCT as well as traditional signal timing strategies are handling anomalies in an efficient manner and meeting agency operational objectives.

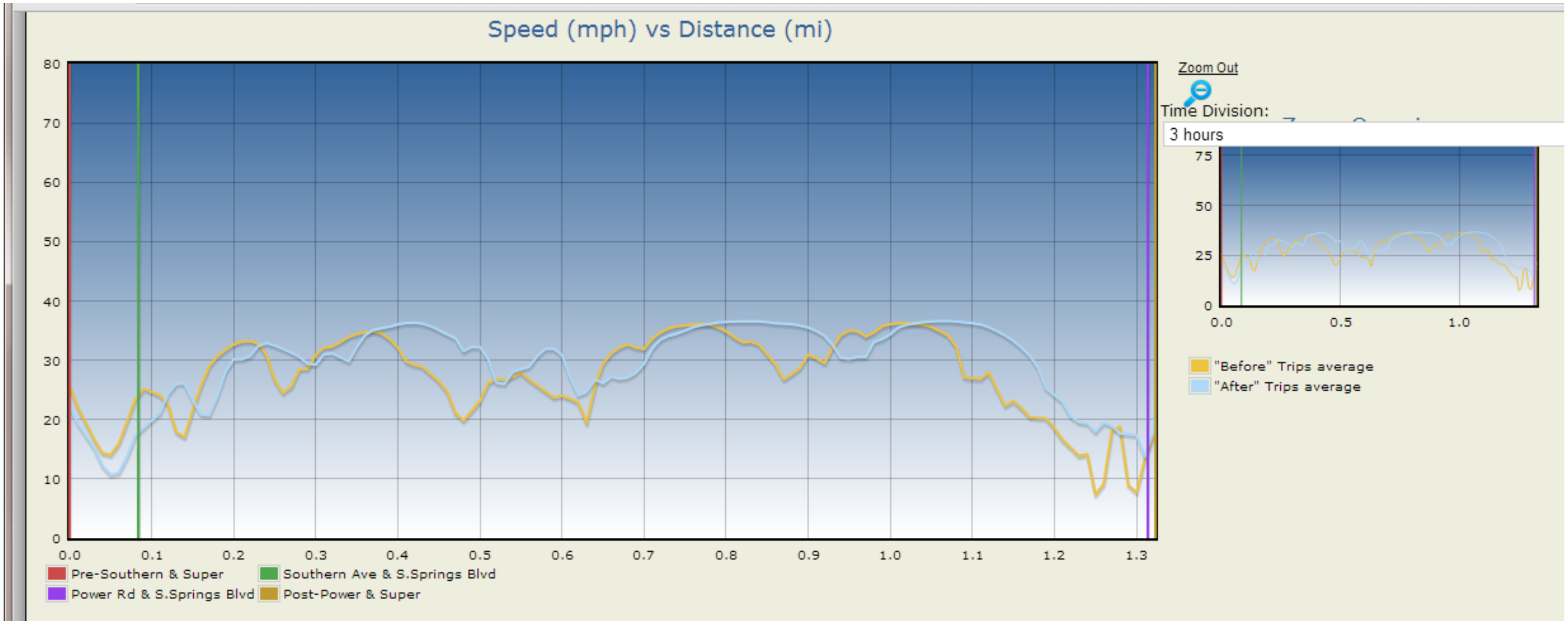
APPENDIX F. ADDITIONAL SUPPORTING DATA FROM THE FIELD TESTING

AVERAGE ROUTE TRAVEL TIME COMPARISONS



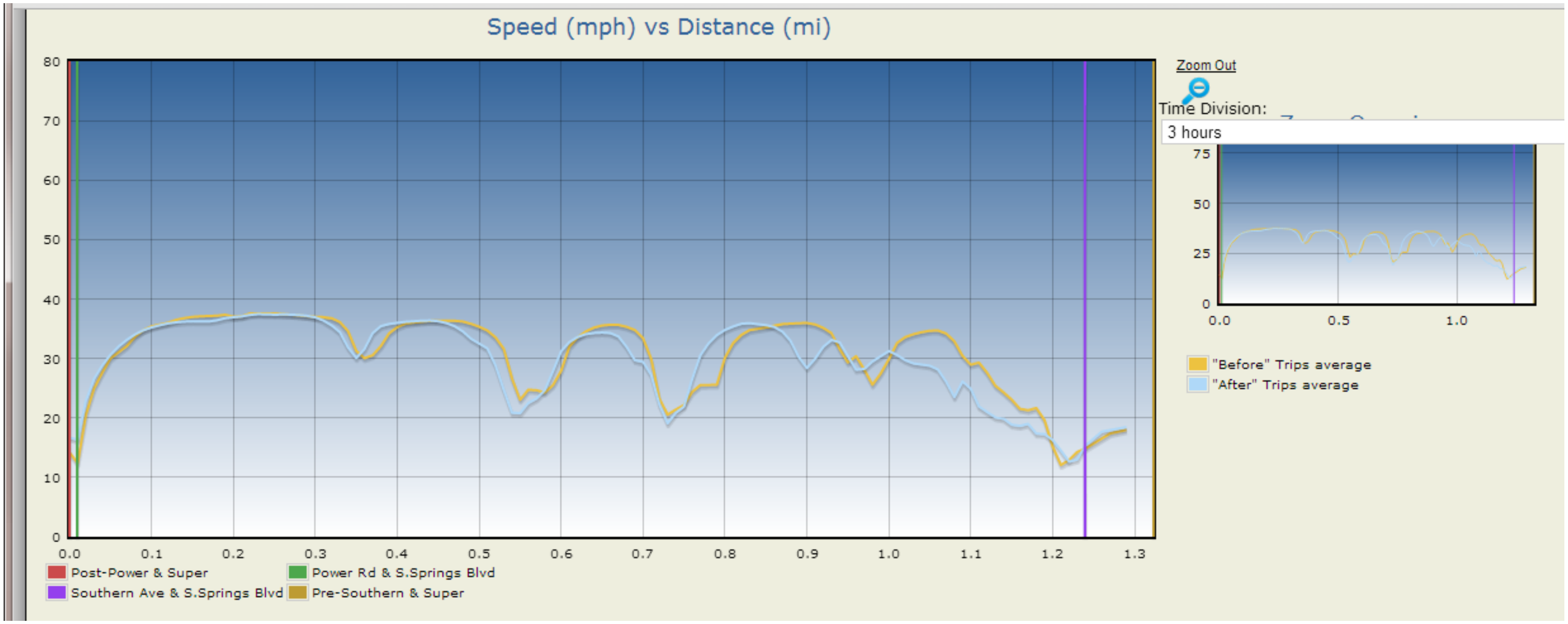
Time Division: 3 hours

Figure 59. Line Graph. Comparison of Average Speed for Route 2
(Source: Kimley-Horn and Associates, Inc.)



Time Division: 3 hours

Figure 60. Line Graph. Comparison of Average Speed for Route 3
(Source: Kimley-Horn and Associates, Inc.)



Time Division: 3 hours

Figure 61. Line Graph. Comparison of Average Speed for Route 4
(Source: Kimley-Horn and Associates, Inc.)

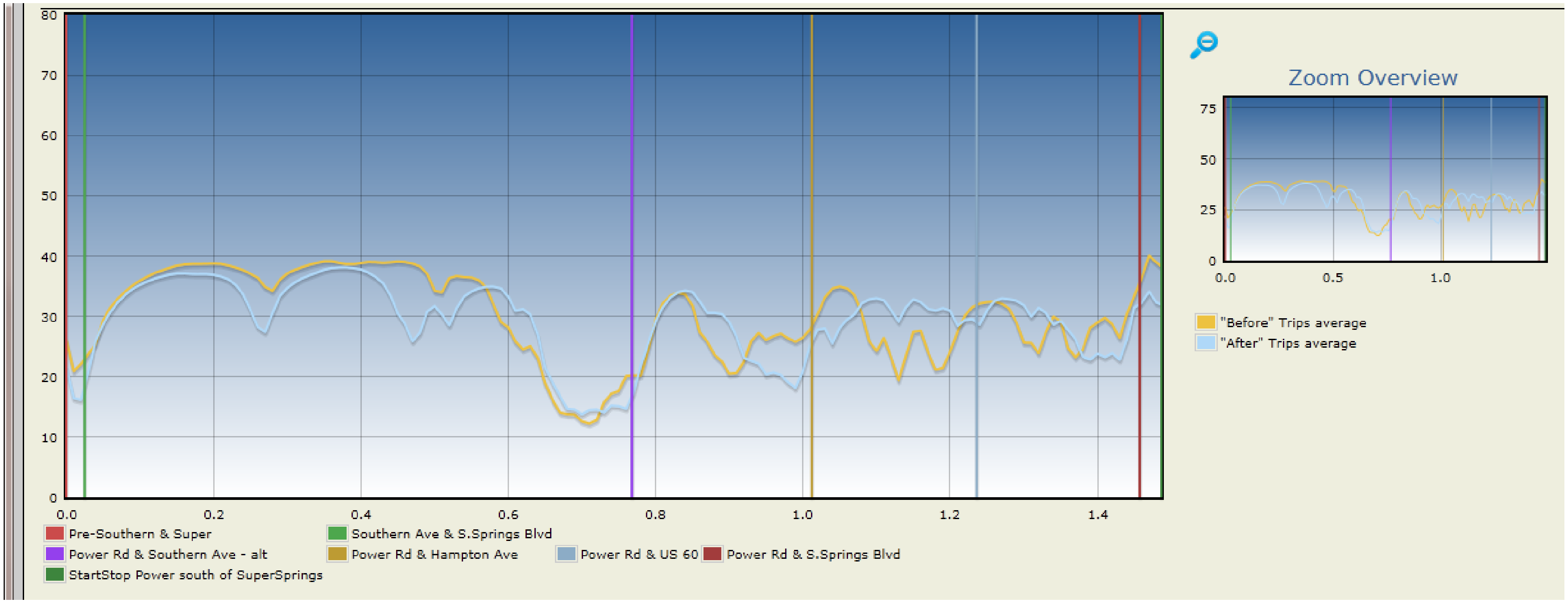


Figure 62. Line Graph. Comparison of Average Speed for Route 5
(Source: Kimley-Horn and Associates, Inc.)

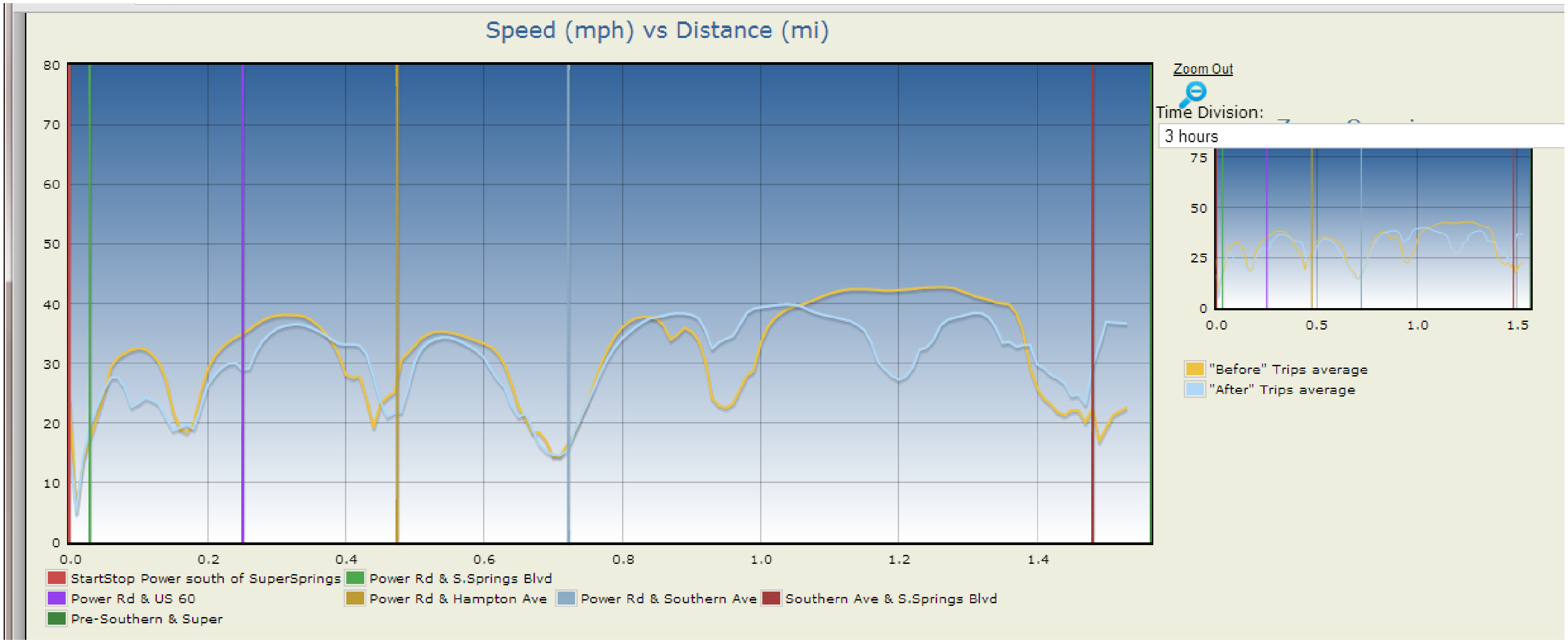


Figure 63. Line Graph. Comparison of Average Speed for Route 6
(Source: Kimley-Horn and Associates, Inc.)

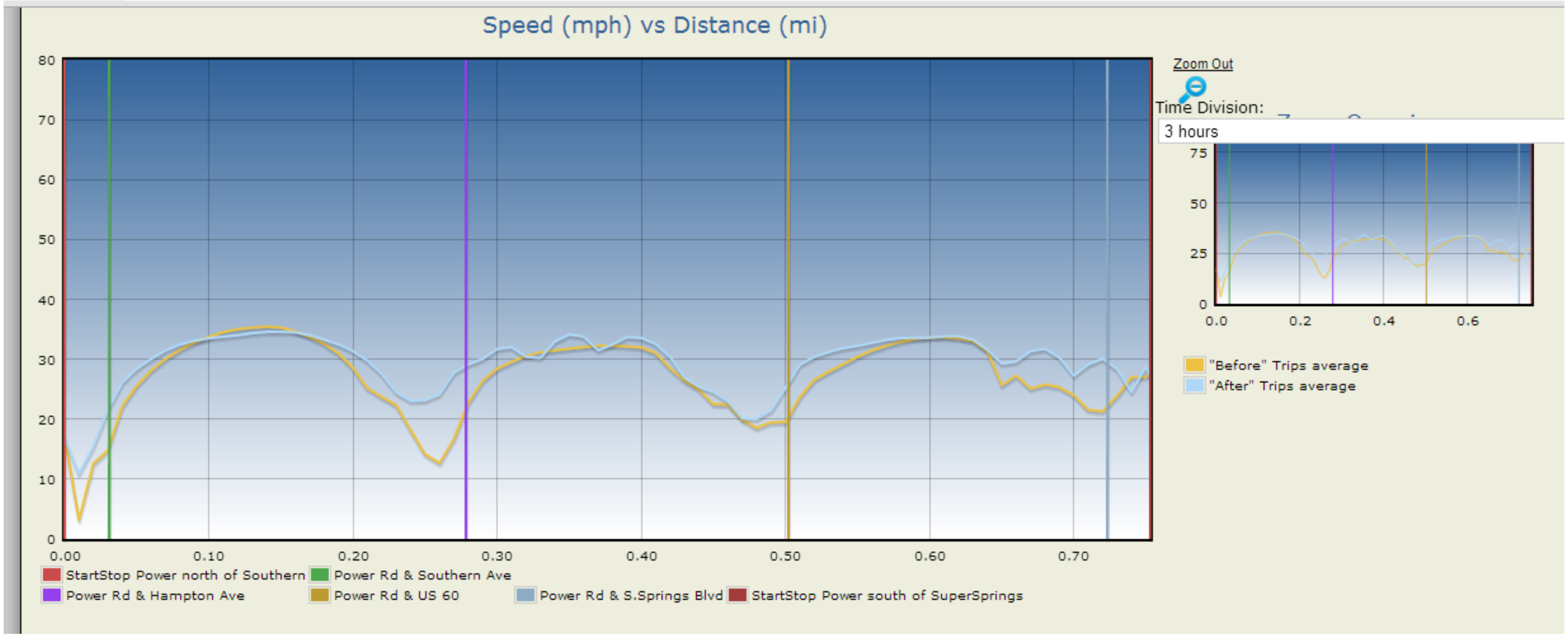
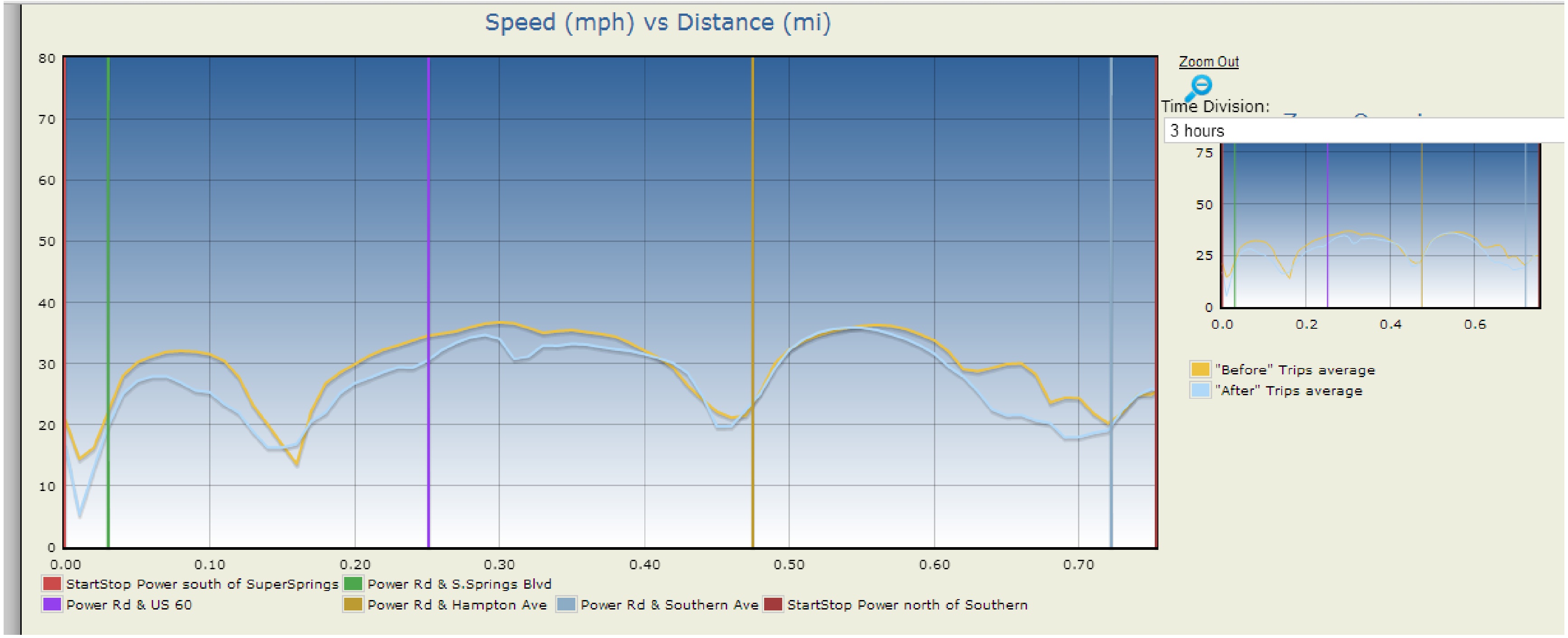


Figure 64. Line Graph. Comparison of Average Speed for Route 7
(Source: Kimley-Horn and Associates, Inc.)



Time Division: 3 hours

Figure 65. Line Graph. Comparison of Average Speed for Route 8
(Source: Kimley-Horn and Associates, Inc.)

APPENDIX G. GREEN OCCUPANCY RATIO PERFORMANCE SUMMARIES

Table 18. Difference between ASCT and Coordination for GOR by Time of Day – Southern and Superstition Springs (Weekends)

	2			**5**			**6**			**8**		
Hour	**Average of GOR**	**GOR Difference**	**StdDev Diff**	**Average of GOR**	**GOR Difference**	**StdDev Diff**	**Average of GOR**	**GOR Difference**	**StdDev Diff**	**Average of GOR**	**GOR Difference**	**StdDev Diff**
7	0.05	0.01	0.01	0.06	-0.01	-0.01	0.06	0.01	0.01	0.50	-0.02	-0.02
8	0.05	0.01	0.01	0.10	-0.02	-0.02	0.07	0.01	0.01	0.47	-0.08	-0.08
9	0.07	-0.01	-0.01	0.15	0.00	0.00	0.10	-0.01	-0.01	0.50	-0.06	-0.06
10	0.09	0.00	0.00	0.14	0.00	0.00	0.13	-0.02	-0.02	0.57	-0.03	-0.03
11	0.11	-0.01	-0.01	0.26	0.02	0.02	0.17	-0.01	-0.01	0.60	-0.02	-0.02
12	0.13	0.00	0.00	0.28	0.02	0.02	0.19	-0.01	-0.01	0.63	0.00	0.00
13	0.12	-0.02	-0.02	0.24	-0.04	-0.04	0.17	-0.03	-0.03	0.64	-0.02	-0.02
14	0.12	-0.02	-0.02	0.24	-0.01	-0.01	0.16	-0.03	-0.03	0.61	-0.03	-0.03
15	0.12	-0.02	-0.02	0.22	0.00	0.00	0.16	-0.04	-0.04	0.62	-0.05	-0.05
16	0.10	-0.02	-0.02	0.21	0.01	0.01	0.14	-0.03	-0.03	0.64	-0.05	-0.05
17	0.11	-0.02	-0.02	0.21	0.01	0.01	0.14	-0.01	-0.01	0.59	-0.07	-0.07
18	0.09	-0.02	-0.02	0.19	0.06	0.06	0.12	-0.01	-0.01	0.61	-0.01	-0.01
19	0.07	-0.01	-0.01	0.09	0.01	0.01	0.09	-0.01	-0.01	0.55	-0.06	-0.06
20	0.06	0.00	0.00	0.07	0.01	0.01	0.07	0.00	0.00	0.58	-0.04	-0.04
21	0.06	0.00	0.00	0.08	0.01	0.01	0.07	0.01	0.01	0.54	-0.04	-0.04
22	0.04	0.00	0.00	0.02	-0.05	-0.05	0.04	0.00	0.00	0.51	-0.06	-0.06

Table 19. Difference between ASCT and Coordination for GOR by Time of Day – Power and Southern (Weekdays)

	1			**2**			**3**			**4**			**5**			**6**			**7**			**8**		
Hour	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**
7	0.71	0.03	0.08	0.34	0.01	0.00	0.74	0.01	0.04	0.38	0.00	-0.01	0.78	0.05	0.02	0.32	0.02	0.01	0.61	-0.09	0.09	0.45	-0.01	-0.02
8	0.72	0.04	0.04	0.35	-0.01	-0.01	0.75	0.02	-0.01	0.42	-0.01	-0.01	0.73	-0.03	0.02	0.35	0.00	-0.02	0.66	-0.02	0.02	0.46	-0.02	-0.01
9	0.76	-0.01	0.02	0.40	0.02	0.01	0.73	-0.04	0.02	0.57	0.02	-0.01	0.70	-0.04	0.03	0.45	0.00	-0.02	0.70	-0.03	0.01	0.52	0.05	-0.01
10	0.81	-0.01	0.01	0.41	-0.01	-0.01	0.74	-0.05	0.02	0.64	-0.02	-0.03	0.71	-0.06	0.03	0.56	0.02	-0.01	0.72	-0.08	0.01	0.54	0.03	-0.02
11	0.85	-0.01	0.01	0.41	0.01	-0.02	0.78	-0.08	0.00	0.72	-0.01	0.01	0.73	-0.06	0.02	0.62	0.08	-0.03	0.68	-0.13	0.00	0.59	0.04	-0.01
12	0.88	-0.02	-0.01	0.39	-0.01	-0.01	0.80	-0.08	0.00	0.75	0.02	-0.01	0.71	-0.09	0.01	0.67	0.05	-0.01	0.64	-0.15	0.01	0.66	0.06	-0.01
13	0.88	0.00	-0.01	0.38	0.01	-0.02	0.81	-0.07	0.00	0.72	0.01	0.01	0.71	-0.08	0.04	0.65	0.07	-0.02	0.65	-0.17	0.00	0.65	0.03	-0.01
14	0.87	-0.01	-0.01	0.35	0.02	-0.02	0.79	-0.09	0.00	0.72	0.00	-0.01	0.68	-0.11	0.03	0.65	0.09	-0.02	0.70	-0.14	-0.01	0.63	0.04	-0.01
16	0.86	0.02	0.00	0.34	-0.02	-0.03	0.81	-0.05	0.00	0.75	0.06	-0.01	0.72	-0.02	0.04	0.68	0.03	-0.05	0.74	-0.09	0.01	0.58	0.03	-0.02
19	0.79	-0.04	0.00	0.24	-0.03	-0.03	0.76	0.00	0.02	0.38	-0.06	-0.04	0.69	-0.07	0.02	0.43	-0.01	0.00	0.64	-0.04	0.06	0.32	0.02	-0.03
20	0.82	-0.02	0.01	0.20	-0.03	-0.01	0.80	0.07	0.04	0.29	-0.05	-0.03	0.74	-0.02	0.01	0.31	-0.03	0.00	0.74	0.06	0.06	0.26	0.01	0.00
21	0.81	-0.02	-0.01	0.17	0.00	0.03	0.79	0.06	0.04	0.22	-0.03	-0.03	0.77	0.01	0.01	0.26	0.00	0.01	0.77	0.08	0.04	0.20	-0.01	-0.01
22	0.87	0.07	-0.01	0.13	0.00	-0.01	0.76	0.05	0.05	0.18	-0.02	-0.03	0.85	0.09	-0.01	0.18	-0.01	0.00	0.76	0.11	0.03	0.18	0.00	0.01

Table 20. Difference between ASCT and Coordination for GOR by Time of Day – Power and Southern (Weekends)

	1			**2**			**3**			**4**			**5**			**6**			**7**			**8**		
	Average GOR	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**
7	0.74	0.10	0.01	0.28	0.07	0.02	0.75	0.10	0.00	0.24	-0.10	-0.01	0.81	0.06	-0.01	0.32	0.11	0.00	0.65	0.02	0.02	0.22	-0.07	-0.06
8	0.75	0.10	0.04	0.32	0.07	-0.01	0.74	0.01	-0.01	0.30	-0.10	-0.01	0.79	0.05	0.02	0.35	0.09	0.01	0.72	0.10	0.01	0.29	-0.01	-0.02
9	0.70	-0.01	-0.01	0.41	0.06	0.02	0.75	-0.02	-0.03	0.48	-0.08	0.02	0.74	0.01	-0.02	0.51	0.11	0.04	0.71	-0.04	0.02	0.37	-0.03	0.00
10	0.75	-0.05	0.01	0.42	0.04	0.05	0.74	-0.15	0.02	0.55	-0.11	0.07	0.74	-0.02	0.01	0.56	0.09	0.04	0.68	-0.12	-0.02	0.44	-0.01	0.02
11	0.83	-0.06	0.02	0.42	0.05	0.02	0.77	-0.18	0.04	0.69	-0.03	0.09	0.73	-0.09	0.02	0.65	0.09	0.03	0.59	-0.25	0.00	0.52	-0.01	0.05
12	0.81	-0.10	0.04	0.41	0.06	0.04	0.79	-0.16	0.01	0.69	-0.03	0.05	0.70	-0.12	0.02	0.65	0.04	0.05	0.49	-0.36	-0.02	0.60	0.05	0.01
13	0.89	-0.05	0.03	0.36	0.02	0.00	0.79	-0.16	0.05	0.71	0.02	0.05	0.71	-0.10	0.04	0.71	0.09	0.01	0.57	-0.26	-0.02	0.64	0.06	0.03
14	0.86	-0.08	0.03	0.35	0.03	0.02	0.81	-0.15	0.06	0.69	0.02	0.04	0.69	-0.09	0.01	0.66	0.07	-0.03	0.53	-0.30	-0.05	0.60	0.02	0.01
16	0.85	-0.05	0.03	0.36	0.07	0.01	0.78	-0.15	0.03	0.64	-0.01	0.02	0.65	-0.11	-0.01	0.64	0.08	0.00	0.57	-0.27	-0.02	0.54	-0.01	0.01
19	0.79	0.05	0.02	0.27	0.06	0.00	0.73	-0.05	0.01	0.35	-0.10	-0.03	0.69	0.03	-0.01	0.49	0.11	-0.02	0.52	-0.14	0.01	0.28	-0.07	-0.05
20	0.78	0.06	-0.01	0.25	0.04	0.00	0.74	0.01	-0.02	0.26	-0.11	-0.06	0.71	0.06	0.03	0.40	0.08	0.00	0.68	0.01	0.04	0.22	-0.10	-0.06
21	0.79	0.08	-0.01	0.25	0.03	-0.06	0.74	0.00	0.04	0.20	-0.09	-0.05	0.74	0.09	0.01	0.35	0.13	0.03	0.63	-0.04	0.04	0.19	-0.07	-0.05
22	0.81	0.11	0.06	0.17	0.01	-0.04	0.74	0.05	-0.01	0.18	-0.06	-0.02	0.80	0.08	0.07	0.24	0.06	0.02	0.68	0.02	0.08	0.14	-0.09	-0.06

Table 21. Difference between ASCT and Coordination for GOR by Time of Day – Power and Hampton (Weekdays)

Hour	**1**			**2**			**3**			**4**			**5**			**6**			**7**			**8**		
	Average GOR	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**
7	0.69	-0.12	0.06	*0.32*	*-0.14*	-0.03	0.64	0.03	0.05	0.34	0.08	0.02	0.71	-0.07	0.02	0.35	-0.19	-0.03	0.71	-0.07	0.04	0.52	0.09	0.01
8	0.65	-0.14	0.04	*0.34*	*-0.12*	-0.03	0.69	-0.04	0.01	0.39	0.09	0.01	0.73	-0.07	0.03	0.37	-0.12	-0.01	0.76	-0.02	0.00	0.56	0.09	0.00
9	0.59	-0.19	0.03	*0.40*	*-0.02*	0.00	0.79	-0.03	-0.01	0.48	0.08	0.00	0.82	-0.05	0.01	0.42	-0.19	0.00	0.78	-0.05	0.05	0.57	0.10	-0.02
10	0.54	-0.28	0.02	*0.48*	*-0.05*	-0.01	0.83	-0.06	-0.02	0.58	0.10	-0.01	0.90	-0.04	-0.01	0.48	-0.14	-0.01	0.80	-0.03	0.02	0.61	0.07	-0.03
11	0.59	-0.24	0.02	*0.53*	*0.02*	-0.01	0.89	0.00	-0.04	0.66	0.12	-0.01	0.95	-0.01	-0.03	0.54	-0.10	0.00	0.85	0.02	0.01	0.70	0.10	-0.03
12	0.63	-0.24	0.02	*0.57*	*0.03*	0.00	0.87	-0.03	0.00	0.68	0.09	-0.06	0.97	0.02	-0.07	0.59	-0.04	-0.01	0.86	0.02	0.01	0.71	0.06	-0.05
13	0.64	-0.23	0.01	*0.60*	*0.05*	0.00	0.87	0.00	-0.04	0.69	0.11	-0.07	0.98	0.02	-0.08	0.59	-0.02	-0.02	0.85	0.00	0.00	0.73	0.08	-0.07
15	0.65	-0.25	0.05	*0.56*	*0.02*	0.05	0.86	0.14	-0.03	0.72	0.00	-0.01	0.97	-0.02	0.03	0.56	-0.14	0.02	0.86	0.05	0.01	0.74	0.03	0.00
16	0.65	-0.30	0.15	*0.57*	*0.03*	0.07	0.85	0.15	-0.02	0.70	0.00	0.02	0.99	0.00	0.00	0.56	-0.10	0.02	0.86	0.03	0.01	0.74	0.02	-0.01
19	0.62	-0.15	-0.01	*0.35*	*-0.03*	0.02	0.74	-0.05	0.02	0.40	0.02	-0.01	0.92	-0.04	0.04	0.50	-0.07	-0.01	0.73	-0.11	0.06	0.40	0.03	-0.02
20	0.69	-0.03	-0.01	*0.26*	*-0.08*	-0.02	0.72	0.01	0.03	0.30	0.03	-0.01	0.89	-0.04	0.03	0.41	-0.11	0.00	0.75	-0.07	0.00	0.28	0.02	-0.01

Table 22. Difference between ASCT and Coordination for GOR by Time of Day – Power and Hampton (Weekends)

	1			**2**			**3**			**4**			**5**			**6**			**7**			**8**		
Hour	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**
7	0.74	0.01	-0.05	0.43	0.00	0.01	0.68	0.03	0.03	0.29	0.09	0.04	0.64	-0.11	0.02	0.48	-0.08	0.05	0.79	-0.03	0.01	0.32	0.05	0.00
8	0.69	-0.09	0.09	0.36	-0.05	-0.04	0.72	0.00	0.02	0.36	0.13	0.06	0.75	0.00	0.00	0.48	-0.08	0.03	0.79	-0.03	0.05	0.39	0.12	0.05
9	0.72	-0.06	-0.01	0.43	-0.04	0.04	0.83	-0.03	0.03	0.47	0.14	0.00	0.83	-0.04	0.02	0.57	-0.03	0.08	0.81	-0.04	0.04	0.49	0.09	0.01
10	0.71	-0.10	0.03	0.50	0.01	0.00	0.92	-0.05	0.04	0.59	0.15	0.03	0.93	-0.01	-0.01	0.60	-0.01	0.03	0.82	0.00	0.00	0.59	0.12	0.02
11	0.80	-0.08	0.06	0.56	0.02	0.00	0.96	-0.02	0.04	0.67	0.13	0.00	0.98	0.00	0.00	0.63	-0.03	0.01	0.88	0.03	0.01	0.70	0.10	0.00
12	0.81	-0.09	0.07	0.60	0.02	0.00	0.97	-0.01	0.02	0.70	0.12	-0.04	0.99	0.00	0.01	0.67	-0.03	0.02	0.85	0.03	-0.02	0.73	0.08	-0.02
13	0.85	-0.06	0.01	0.65	0.08	-0.01	0.96	-0.01	0.00	0.72	0.11	-0.03	0.99	0.00	-0.01	0.74	0.01	0.02	0.89	0.03	-0.01	0.76	0.05	-0.02
15	0.83	-0.07	0.05	0.62	0.02	0.00	0.96	-0.02	0.03	0.71	0.11	-0.02	1.00	0.00	0.01	0.60	-0.05	0.01	0.90	0.01	-0.02	0.80	0.06	-0.01
16	0.79	-0.10	0.06	0.57	0.02	0.02	0.92	-0.03	0.03	0.66	0.07	-0.04	0.99	0.00	-0.01	0.69	0.02	0.04	0.92	0.01	-0.01	0.76	0.01	0.01
19	0.69	-0.10	0.03	0.36	0.00	0.03	0.82	0.01	-0.05	0.43	0.08	0.00	0.94	-0.01	0.01	0.52	-0.07	-0.03	0.79	-0.01	0.01	0.40	0.05	-0.03
20	0.69	-0.06	0.01	0.26	-0.06	-0.04	0.77	0.03	-0.01	0.32	0.08	0.02	0.89	-0.04	0.03	0.53	-0.01	-0.01	0.77	-0.05	0.08	0.33	0.07	0.03

Table 23. Difference between ASCT and Coordination for GOR by Time of Day – Power and U.S. 60 (Weekdays)

	1			2			3			4			5			6			7			8		
Hour	Average GOR	GOR Difference	StdDev Diff	Average GOR	GOR Difference	StdDev Diff	Average GOR	GOR Difference	StdDev Diff	Average GOR	GOR Difference	StdDev Diff	Average GOR	GOR Difference	StdDev Diff	Average GOR	GOR Difference	StdDev Diff	Average GOR	GOR Difference	StdDev Diff	Average GOR	GOR Difference	StdDev Diff
7	0.62	0.02	0.00	0.00	0.00	0.06	0.31	0.03	0.02	0.59	0.00	0.00	0.13	0.13	0.27	0.52	0.10	0.03	0.62	0.02	0.00	0.00	0.00	0.06
8	0.68	0.01	0.00	0.00	0.00	0.00	0.33	0.03	0.03	0.53	-0.05	-0.01	0.18	0.18	0.31	0.59	0.16	0.06	0.68	0.01	0.00	0.00	0.00	0.00
9	0.67	-0.01	0.00	0.00	0.00	0.07	0.38	0.02	0.01	0.51	-0.06	-0.02	0.16	0.16	0.31	0.57	0.12	0.03	0.67	-0.01	0.00	0.00	0.00	0.07
10	0.66	-0.04	-0.03	0.00	0.00	0.00	0.46	0.00	-0.01	0.50	-0.12	-0.03	0.24	0.24	0.36	0.62	0.11	0.03	0.66	-0.04	-0.03	0.00	0.00	0.00
11	0.72	-0.03	-0.01	0.00	0.00	0.00	0.55	-0.01	-0.02	0.53	-0.07	-0.02	0.18	0.18	0.34	0.67	0.09	0.01	0.72	-0.03	-0.01	0.00	0.00	0.00
12	0.72	-0.02	-0.03	0.00	0.00	0.00	0.59	-0.05	-0.03	0.55	-0.06	-0.03	0.26	0.26	0.38	0.72	0.07	0.00	0.72	-0.02	-0.03	0.00	0.00	0.00
13	0.77	-0.01	-0.03	0.00	0.00	0.06	0.61	-0.01	-0.04	0.53	-0.07	-0.02	0.19	0.19	0.34	0.68	0.04	0.00	0.77	-0.01	-0.03	0.00	0.00	0.06
14	0.77	-0.02	-0.03	0.00	0.00	0.06	0.63	-0.02	-0.05	0.56	-0.09	-0.03	0.20	0.20	0.29	0.68	0.05	0.00	0.77	-0.02	-0.03	0.00	0.00	0.06
15	0.74	-0.02	-0.01	0.00	0.00	0.00	0.61	0.03	-0.05	0.62	-0.05	-0.02	0.34	0.31	0.25	0.75	0.13	-0.01	0.74	-0.02	-0.01	0.00	0.00	0.00
16	0.76	0.00	0.00	0.01	0.01	0.10	0.66	0.04	-0.05	0.63	-0.07	0.00	0.44	0.40	0.24	0.77	0.15	-0.01	0.76	0.00	0.00	0.01	0.01	0.10
17	0.71	-0.02	-0.01	0.00	0.00	0.03	0.66	0.07	-0.06	0.64	-0.07	0.00	0.26	0.24	0.25	0.69	0.14	0.01	0.71	-0.02	-0.01	0.00	0.00	0.03
18	0.68	0.00	-0.02	0.01	0.01	0.10	0.59	0.04	-0.02	0.59	-0.07	-0.02	0.19	0.17	0.23	0.58	0.07	0.03	0.68	0.00	-0.02	0.01	0.01	0.10
19	0.63	-0.02	0.02	0.00	0.00	0.05	0.44	0.00	0.03	0.53	-0.10	0.00	0.04	0.04	0.17	0.38	0.03	0.04	0.63	-0.02	0.02	0.00	0.00	0.05
20	0.54	-0.03	0.00	0.00	0.00	0.00	0.33	-0.02	0.01	0.48	-0.04	-0.02	0.03	0.03	0.15	0.28	-0.01	0.02	0.54	-0.03	0.00	0.00	0.00	0.00
21	0.53	0.02	-0.01	0.00	0.00	0.00	0.28	-0.01	0.03	0.49	-0.05	-0.01	0.02	0.02	0.13	0.25	0.00	0.02	0.53	0.02	-0.01	0.00	0.00	0.00
22	0.45	0.01	0.00	0.00	0.00	0.00	0.20	0.03	0.04	0.45	-0.02	-0.01	0.04	0.04	0.14	0.22	0.05	0.07	0.45	0.01	0.00	0.00	0.00	0.00

Table 24. Difference between ASCT and Coordination for GOR by Time of Day – Power and U.S. 60 (Weekends)

	1			**2**			**3**			**4**			**5**			**6**			**7**			**8**		
Hour	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**
7	0.53	-0.06	0.03	0.01	0.01	0.08	0.24	0.08	0.06	0.52	-0.02	-0.02	0.15	0.15	0.28	0.32	0.12	0.06	0.53	-0.06	0.03	0.01	0.01	0.08
8	0.53	-0.03	0.01	0.00	0.00	0.00	0.26	0.05	0.02	0.57	-0.03	0.01	0.21	0.21	0.32	0.37	0.13	0.05	0.53	-0.03	0.01	0.00	0.00	0.00
9	0.57	-0.03	0.02	0.00	0.00	0.06	0.34	0.03	-0.01	0.60	-0.01	0.00	0.19	0.19	0.32	0.44	0.07	-0.01	0.57	-0.03	0.02	0.00	0.00	0.06
10	0.57	-0.05	0.00	0.00	0.00	0.00	0.40	-0.03	0.00	0.66	-0.03	-0.02	0.34	0.34	0.39	0.57	0.07	0.01	0.57	-0.05	0.00	0.00	0.00	0.00
11	0.62	-0.05	-0.01	0.01	0.01	0.10	0.52	-0.05	-0.02	0.65	-0.05	-0.01	0.30	0.30	0.39	0.63	0.01	-0.01	0.62	-0.05	-0.01	0.01	0.01	0.10
12	0.67	-0.02	0.00	0.00	0.00	0.00	0.57	-0.08	-0.03	0.69	-0.01	0.00	0.30	0.30	0.40	0.70	0.03	-0.01	0.67	-0.02	0.00	0.00	0.00	0.00
13	0.71	0.00	-0.01	0.00	0.00	0.00	0.61	-0.07	-0.02	0.68	-0.02	0.00	0.26	0.26	0.38	0.71	0.01	0.00	0.71	0.00	-0.01	0.00	0.00	0.00
14	0.70	-0.01	-0.02	0.00	0.00	0.03	0.59	-0.08	0.00	0.65	-0.02	-0.02	0.27	0.27	0.39	0.69	0.03	0.01	0.70	-0.01	-0.02	0.00	0.00	0.03
15	0.72	0.01	0.00	0.00	0.00	0.07	0.58	-0.09	-0.02	0.65	-0.05	-0.01	0.25	0.25	0.37	0.66	0.00	-0.01	0.72	0.01	0.00	0.00	0.00	0.07
16	0.71	-0.01	0.00	0.00	0.00	0.00	0.54	-0.14	-0.02	0.69	-0.03	0.00	0.39	0.39	0.43	0.64	0.00	0.00	0.71	-0.01	0.00	0.00	0.00	0.00
17	0.70	0.01	-0.01	0.00	0.00	0.07	0.56	-0.12	-0.03	0.71	0.02	-0.02	0.24	0.24	0.37	0.58	-0.01	-0.01	0.70	0.01	-0.01	0.00	0.00	0.07
18	0.69	-0.01	0.00	0.00	0.00	0.06	0.55	-0.07	-0.01	0.71	0.03	-0.02	0.13	0.13	0.29	0.54	-0.02	-0.01	0.69	-0.01	0.00	0.00	0.00	0.06
19	0.59	0.02	0.00	0.00	0.00	0.00	0.43	-0.04	-0.01	0.68	0.07	-0.01	0.08	0.08	0.23	0.42	0.02	0.00	0.59	0.02	0.00	0.00	0.00	0.00
20	0.52	-0.04	-0.01	0.00	0.00	0.06	0.35	0.02	0.00	0.58	0.01	-0.01	0.12	0.12	0.28	0.35	0.06	0.02	0.52	-0.04	-0.01	0.00	0.00	0.06
21	0.53	-0.02	0.01	0.00	0.00	0.00	0.31	0.05	0.02	0.64	0.00	0.00	0.09	0.09	0.24	0.31	0.06	0.03	0.53	-0.02	0.01	0.00	0.00	0.00
22	0.45	-0.01	0.01	0.00	0.00	0.00	0.24	0.08	0.08	0.55	-0.07	0.00	0.10	0.10	0.24	0.31	0.11	0.09	0.45	-0.01	0.01	0.00	0.00	0.00

Table 25. Difference between ASCT and Coordination for GOR by Time of Day – Power and Superstition Springs (Weekdays)

Hour	1			2			3			4			5			6			7			8		
	Average GOR	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**
7	0.69	-0.14	0.26	0.45	-0.23	-0.01	0.87	0.02	0.00	0.50	-0.03	-0.09	0.75	-0.02	0.10	0.25	-0.20	-0.04	0.78	0.14	-0.09	0.54	0.01	-0.01
8	0.68	-0.12	0.18	0.57	-0.08	-0.02	0.84	-0.06	0.02	0.43	-0.08	-0.06	0.55	-0.24	0.20	0.34	-0.11	-0.03	0.82	0.16	-0.02	0.54	-0.01	0.00
9	0.73	-0.05	0.09	0.51	-0.06	-0.02	0.80	-0.05	0.08	0.46	-0.05	-0.10	0.54	-0.24	0.12	0.38	-0.09	-0.06	0.66	0.00	0.00	0.50	-0.03	-0.02
10	0.72	-0.07	0.11	0.53	-0.08	-0.06	0.82	-0.04	0.01	0.47	-0.08	-0.09	0.63	-0.16	0.13	0.50	-0.03	-0.01	0.74	0.03	-0.07	0.52	-0.07	-0.02
11	0.80	0.00	0.03	0.47	-0.13	-0.05	0.86	-0.03	0.01	0.50	-0.07	-0.06	0.63	-0.18	0.11	0.53	-0.04	-0.05	0.73	0.04	-0.04	0.62	-0.06	-0.04
12	0.74	-0.08	0.05	0.48	-0.14	-0.05	0.89	-0.02	0.02	0.50	-0.17	-0.04	0.62	-0.21	0.11	0.53	-0.11	-0.02	0.74	0.02	-0.08	0.69	-0.03	-0.03
13	0.76	-0.07	0.04	0.43	-0.18	-0.05	0.86	-0.02	0.02	0.58	0.00	-0.04	0.63	-0.17	0.06	0.52	-0.06	-0.01	0.80	0.11	-0.06	0.62	-0.04	-0.01
14	0.79	-0.02	0.02	0.31	-0.25	-0.08	0.78	-0.08	0.02	0.60	-0.01	-0.06	0.66	-0.15	0.07	0.46	-0.14	-0.04	0.70	0.01	-0.06	0.71	0.01	0.01
15	0.81	0.01	0.04	0.40	-0.12	-0.08	0.84	-0.04	0.04	0.58	0.00	-0.07	0.57	-0.19	0.06	0.52	-0.09	-0.05	0.75	0.06	-0.03	0.70	0.00	-0.05
16	0.78	-0.02	0.02	0.35	-0.18	-0.09	0.95	0.06	-0.04	0.67	0.05	-0.08	0.61	-0.16	0.03	0.46	-0.16	-0.07	0.77	0.11	-0.02	0.77	0.07	-0.06
17	0.85	0.04	0.04	0.31	-0.24	-0.12	0.89	0.00	0.03	0.74	0.11	-0.05	0.68	-0.12	0.06	0.47	-0.14	-0.08	0.82	0.12	-0.03	0.78	0.08	-0.09
18	0.70	-0.09	0.03	0.34	-0.17	-0.07	0.86	0.00	0.02	0.60	0.06	-0.04	0.57	-0.17	0.02	0.48	-0.09	-0.08	0.81	0.07	-0.01	0.62	0.01	-0.05
19	0.80	0.01	0.02	0.36	-0.19	-0.05	0.79	-0.07	0.06	0.39	-0.06	-0.03	0.58	-0.19	0.07	0.41	-0.07	-0.02	0.79	0.15	0.00	0.45	-0.02	-0.01
20	0.77	0.01	0.03	0.39	-0.08	0.00	0.84	0.01	0.04	0.35	0.01	-0.01	0.70	-0.05	0.08	0.49	0.03	-0.01	0.74	0.17	0.03	0.34	-0.01	-0.03
21	0.78	0.04	-0.01	0.39	-0.04	0.01	0.76	-0.05	0.08	0.26	0.01	0.00	0.63	-0.09	0.05	0.36	-0.14	-0.06	0.78	0.21	0.04	0.31	0.02	-0.02
22	0.82	0.15	-0.03	0.35	-0.05	0.01	0.75	-0.08	0.01	0.15	-0.01	-0.01	0.73	0.04	-0.06	0.38	-0.05	-0.04	0.73	0.19	-0.03	0.16	-0.02	-0.06

Table 26. Difference between ASCT and Coordination for GOR by Time of Day – Power and Superstition Springs (Weekends)

Hour	1			2			3			4			5			6			7			8		
	Average GOR	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**	**Average GOR**	**GOR Difference**	**StdDev Diff**
7	0.75	0.02	0.08	0.44	-0.04	-0.01	0.77	-0.05	0.06	0.19	-0.08	-0.03	0.79	0.06	0.01	0.30	-0.08	-0.06	0.87	0.32	-0.07	0.22	-0.03	-0.02
8	0.82	0.06	-0.02	0.37	-0.15	-0.03	0.74	-0.08	0.04	0.29	-0.01	0.03	0.76	0.02	0.10	0.36	-0.07	-0.03	0.71	0.15	0.03	0.29	-0.04	-0.02
9	0.76	-0.02	0.14	0.48	-0.08	-0.01	0.72	-0.12	0.06	0.37	-0.02	-0.01	0.78	-0.01	0.05	0.39	-0.07	-0.02	0.73	0.09	0.03	0.42	-0.05	-0.03
10	0.65	-0.16	0.12	0.44	-0.11	0.00	0.80	-0.06	0.02	0.39	-0.06	-0.05	0.58	-0.22	0.13	0.45	-0.08	0.01	0.78	0.09	-0.04	0.53	-0.04	-0.01
11	0.76	-0.04	0.05	0.55	-0.02	-0.03	0.80	-0.08	0.04	0.43	-0.10	-0.06	0.61	-0.17	0.08	0.56	-0.02	-0.03	0.75	0.01	-0.04	0.53	-0.11	-0.08
12	0.79	-0.02	0.03	0.49	-0.14	-0.05	0.84	-0.04	0.01	0.49	-0.09	-0.05	0.65	-0.14	0.04	0.50	-0.13	-0.03	0.71	-0.03	-0.02	0.65	-0.06	0.00
13	0.81	-0.03	0.11	0.38	-0.28	-0.05	0.83	-0.05	0.05	0.54	-0.06	-0.03	0.66	-0.16	0.12	0.59	-0.03	0.00	0.77	-0.02	0.00	0.72	-0.02	0.01
14	0.72	-0.11	0.06	0.39	-0.19	-0.02	0.79	-0.08	0.02	0.52	-0.04	-0.04	0.62	-0.20	0.09	0.62	0.01	-0.08	0.73	-0.04	-0.06	0.63	-0.06	-0.01
15	0.73	-0.06	0.06	0.45	-0.13	-0.06	0.82	-0.08	0.05	0.46	-0.07	-0.07	0.66	-0.15	0.10	0.51	-0.11	-0.02	0.70	-0.11	-0.01	0.64	-0.06	-0.01
16	0.80	0.00	0.06	0.47	-0.16	-0.07	0.83	-0.05	0.00	0.50	-0.06	-0.07	0.64	-0.18	0.14	0.49	-0.13	-0.07	0.77	-0.03	-0.03	0.60	-0.07	-0.05
17	0.84	0.02	0.07	0.49	-0.15	-0.02	0.81	-0.07	0.03	0.46	-0.07	-0.03	0.78	-0.02	0.03	0.47	-0.16	-0.01	0.73	-0.04	-0.03	0.52	-0.13	-0.02
18	0.79	-0.01	0.05	0.35	-0.24	-0.02	0.82	-0.04	0.07	0.47	-0.02	-0.07	0.64	-0.19	0.14	0.47	-0.13	0.03	0.81	0.05	0.01	0.51	-0.10	-0.08
19	0.75	-0.04	0.06	0.41	-0.14	-0.01	0.79	-0.05	0.04	0.39	0.02	-0.03	0.59	-0.19	0.08	0.40	-0.15	0.04	0.77	0.04	0.04	0.38	-0.06	-0.06
20	0.81	0.01	0.06	0.36	-0.15	-0.04	0.81	-0.04	0.04	0.29	-0.02	-0.04	0.68	-0.09	0.08	0.42	-0.09	0.00	0.77	0.14	0.03	0.29	-0.06	-0.05
21	0.86	0.07	0.00	0.30	-0.18	-0.02	0.76	-0.06	0.07	0.22	0.00	-0.01	0.77	0.02	0.04	0.33	-0.15	-0.02	0.80	0.19	-0.05	0.22	-0.06	-0.03
22	0.77	0.03	0.08	0.36	-0.09	-0.03	0.85	0.01	0.11	0.19	0.03	0.06	0.72	-0.06	0.07	0.38	-0.08	-0.03	0.80	0.21	0.09	0.22	0.02	0.05

APPENDIX H. THROUGHPUT PERFORMANCE METRICS

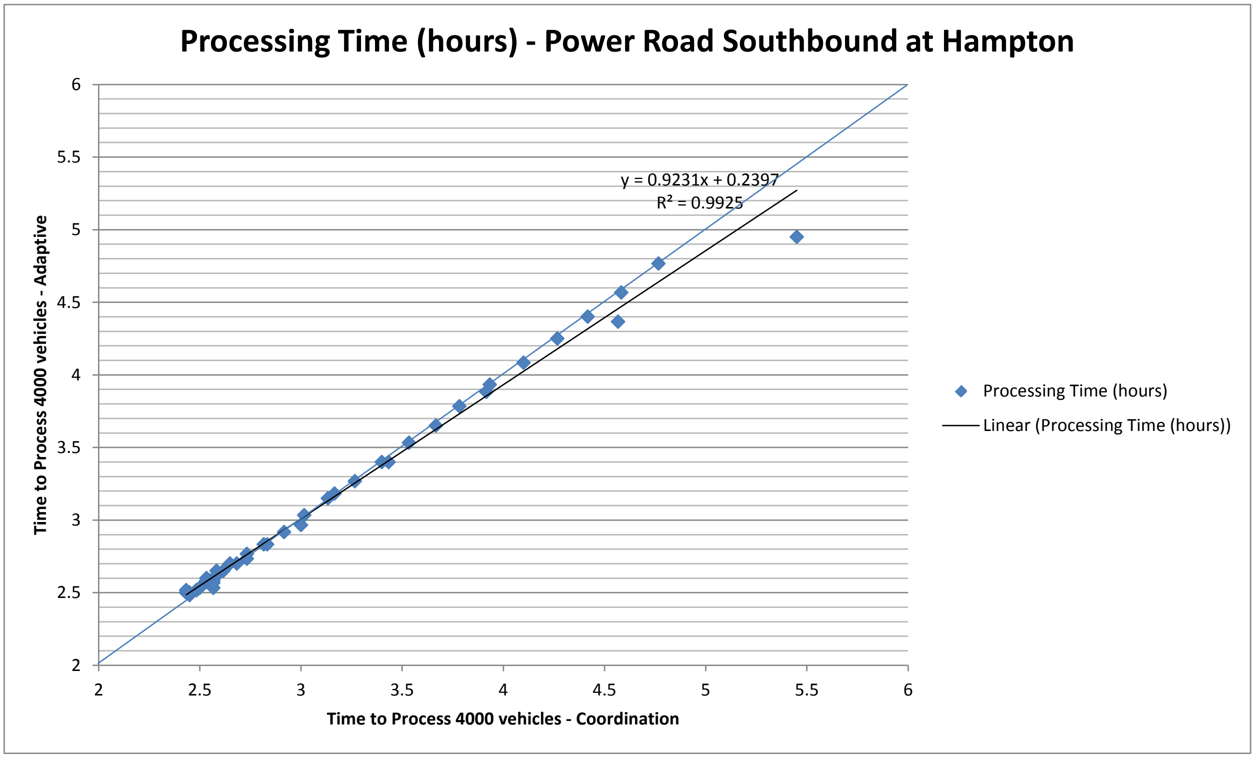


Figure 66. Line Graph. Throughput Performance for ASCT versus Coordination – Volume Counter "C", Southbound
(Source: Kimley-Horn and Associates, Inc.)

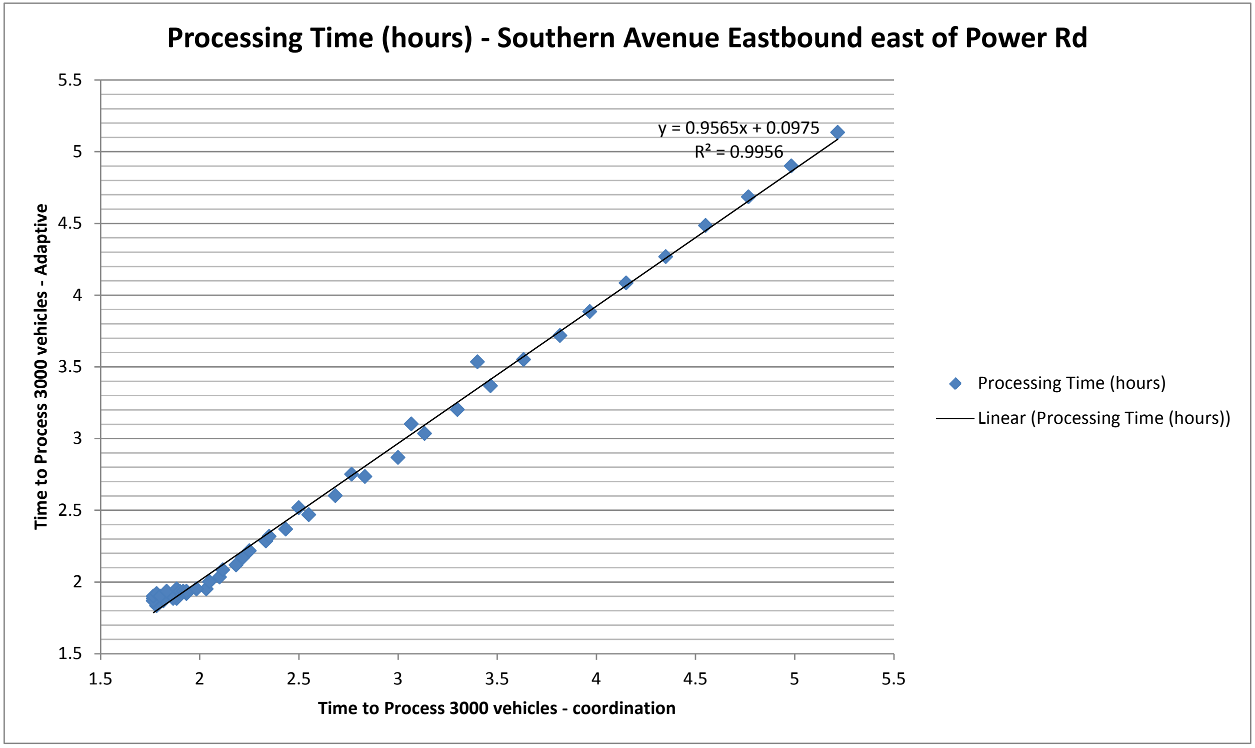


Figure 67. Line Graph. Throughput Performance for ASCT versus Coordination – Volume Counter "B", Eastbound
(Source: Kimley-Horn and Associates, Inc.)

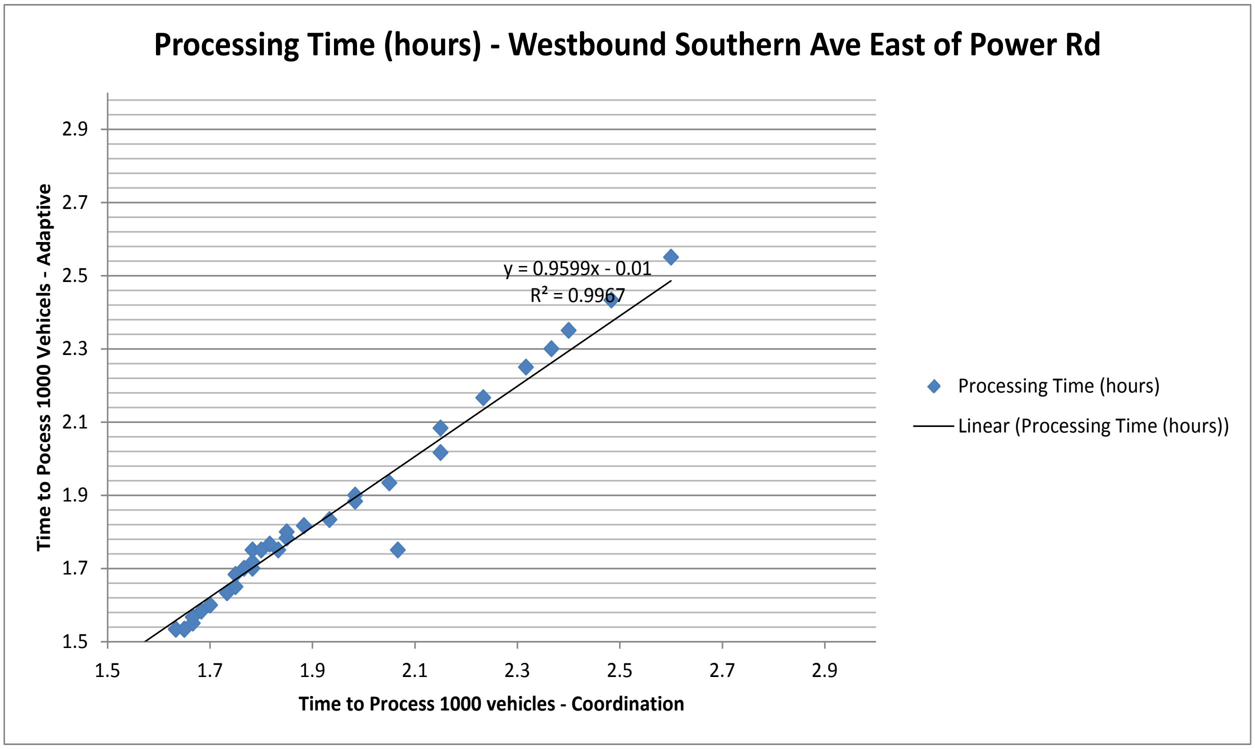


Figure 68. Line Graph. Throughput Performance for ASCT versus Coordination – Volume Counter "B", Westbound
(Source: Kimley-Horn and Associates, Inc.)

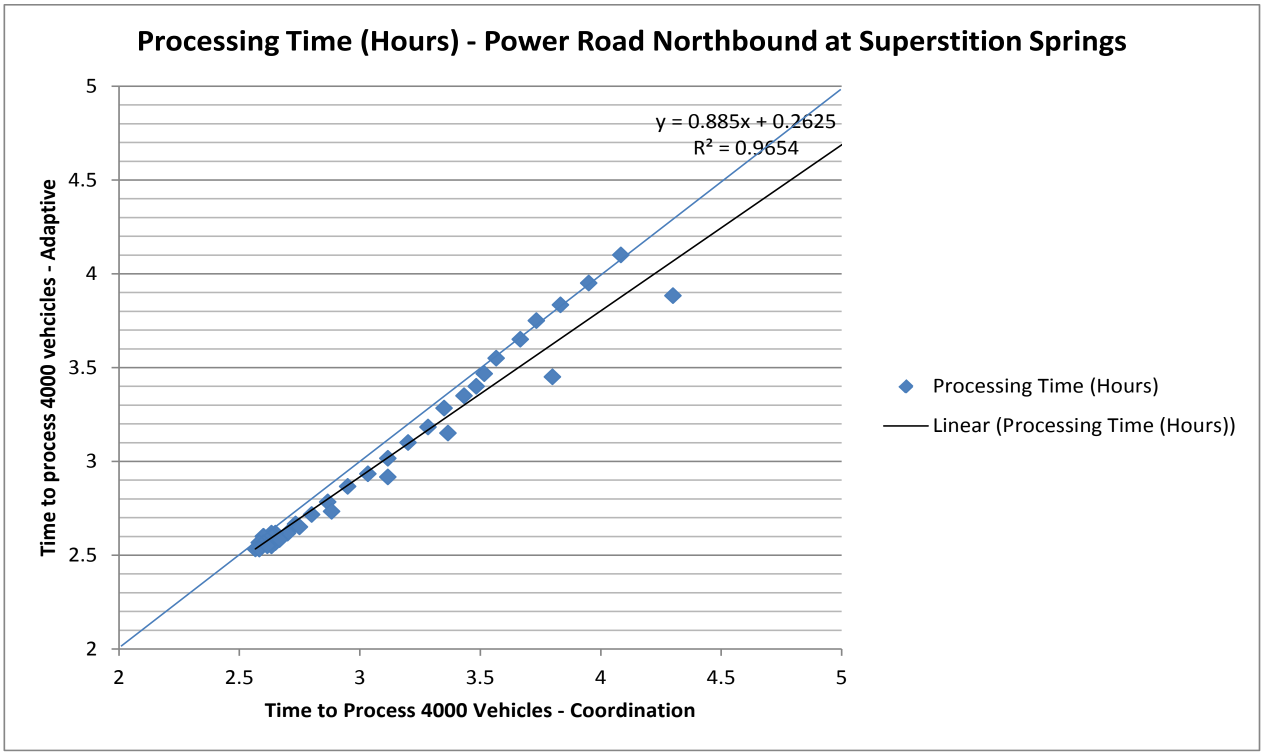


Figure 69. Line Graph. Throughput Performance for ASCT versus Coordination – Volume Counter "D", Northbound
(Source: Kimley-Horn and Associates, Inc.)

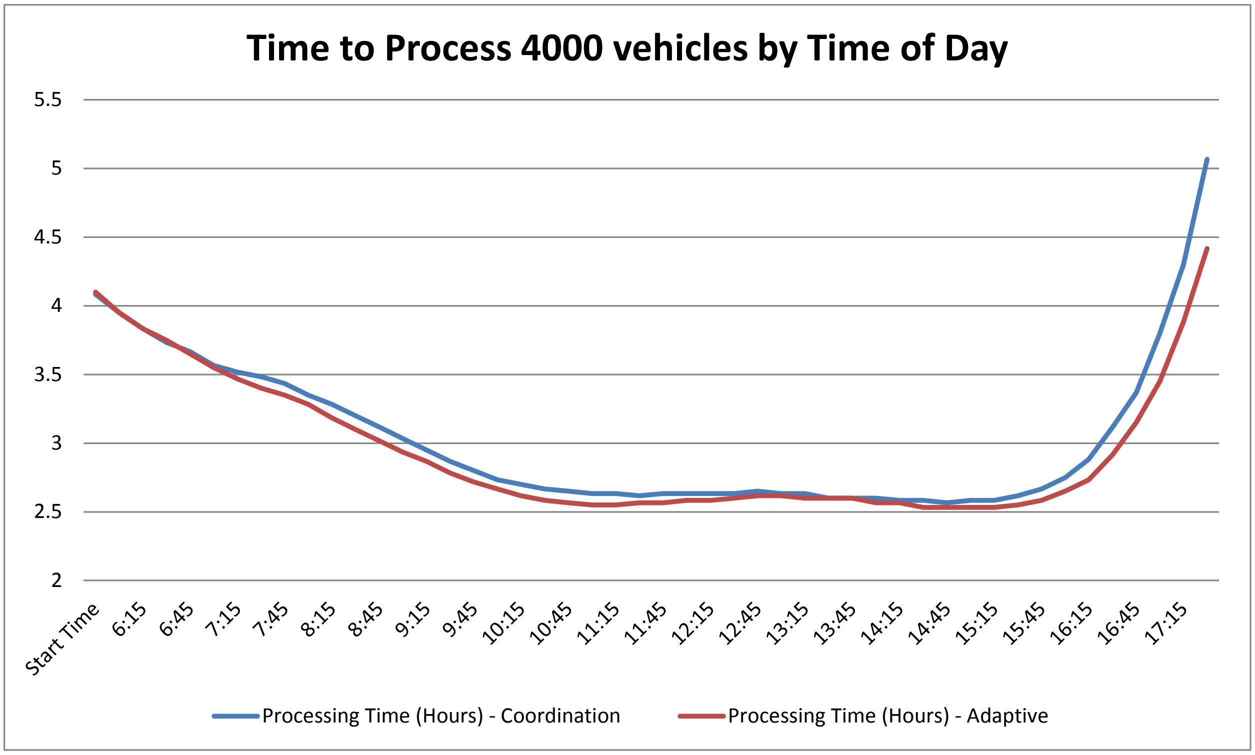


Figure 70. Line Graph. Throughput Performance by Time of Day –
Volume Counter ”D”, Northbound
(Source: Kimley-Horn and Associates, Inc.)

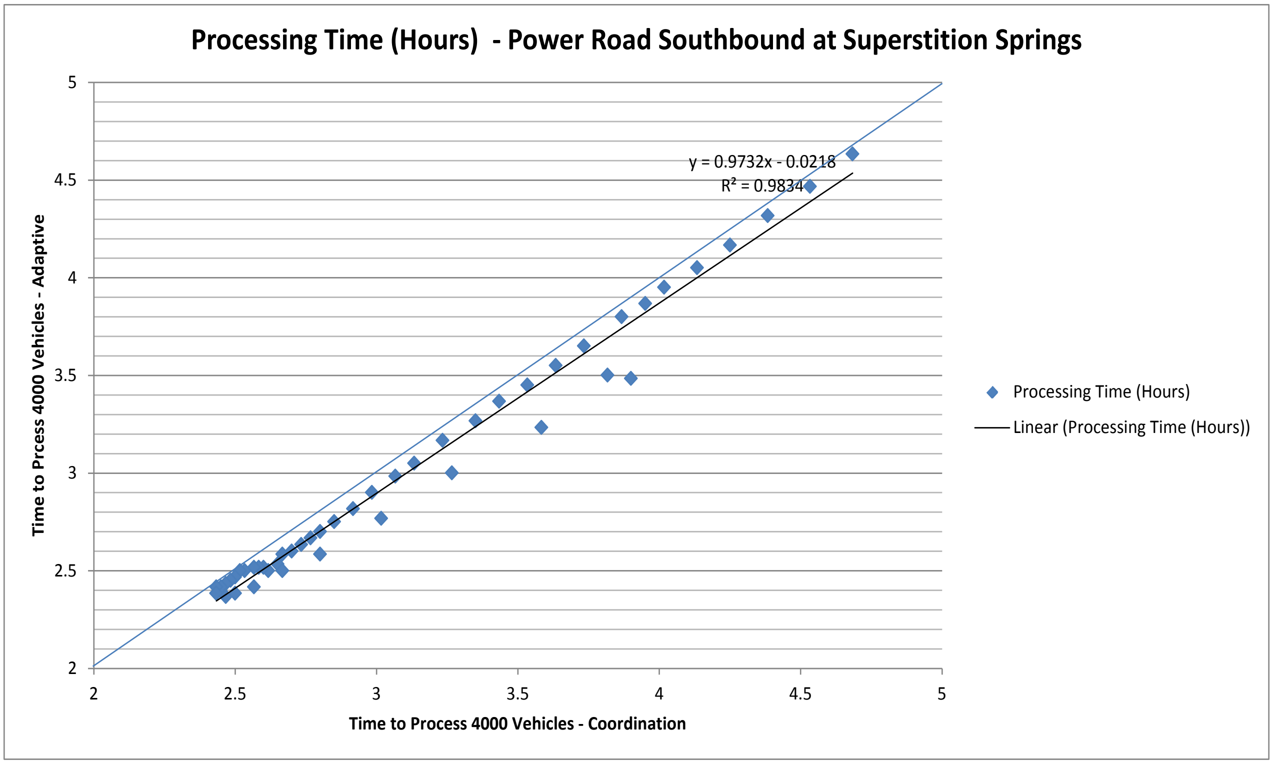


Figure 71. Line Graph. Throughput Performance for ASCT versus Coordination – Volume Counter "D", Southbound
(Source: Kimley-Horn and Associates, Inc.)

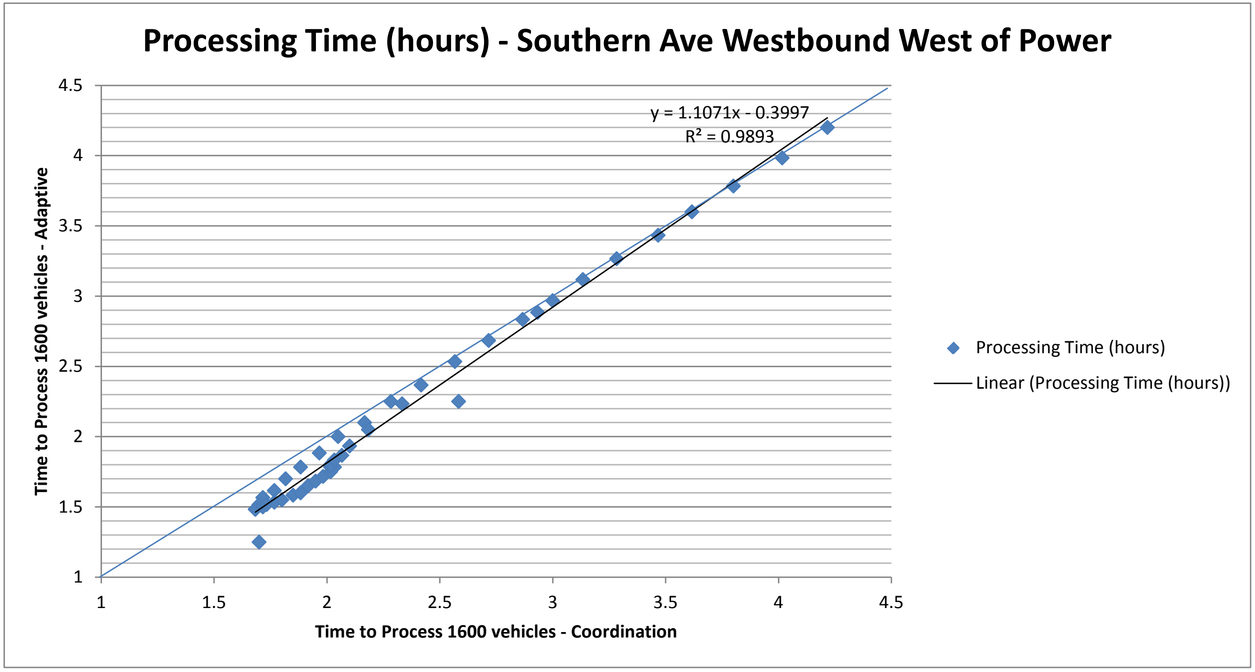


Figure 72. Line Graph. Throughput Performance for ASCT versus Coordination – Volume Counter "A", Westbound
(Source: Kimley-Horn and Associates, Inc.)

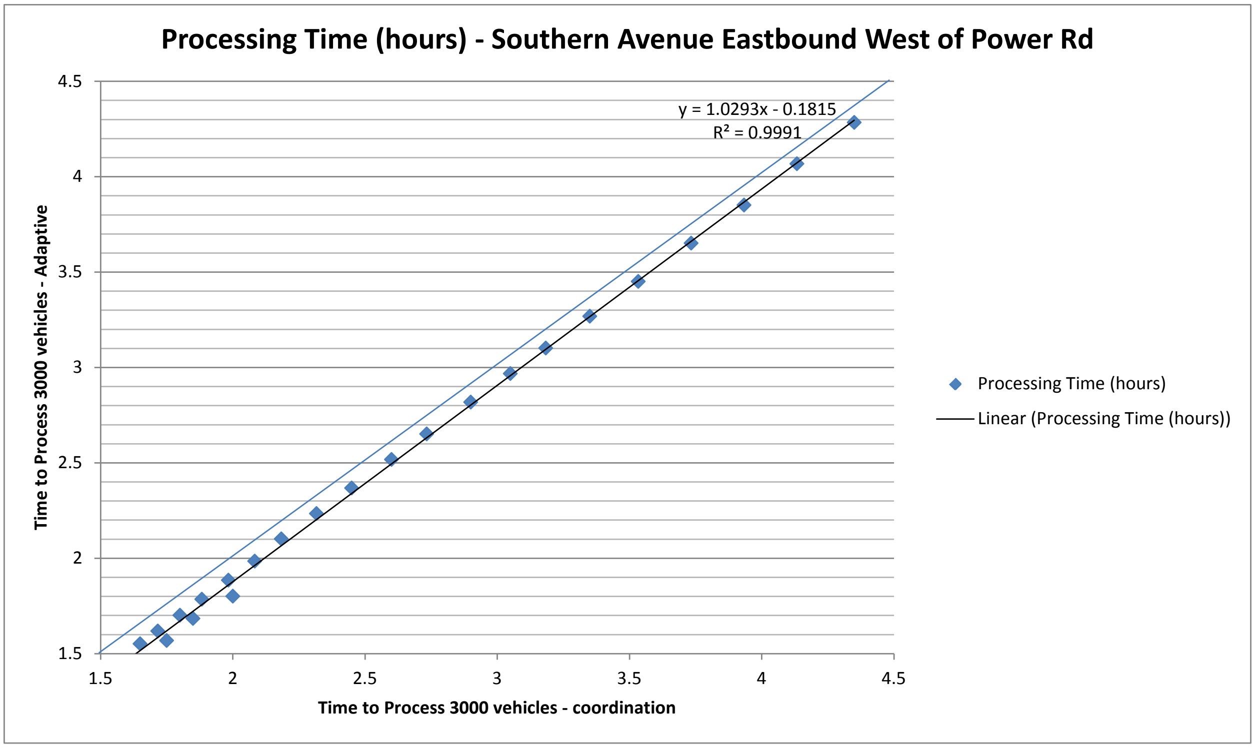


Figure 73. Line Graph. Throughput Performance for ASCT versus Coordination – Volume Counter "A", Eastbound
(Source: Kimley-Horn and Associates, Inc.)

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July 2013

FHWA-HOP-13-031