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17. Key Words: traffic signal, adaptive traffic signal control, adaptive control systems, performance measures, link-pivot algorithm

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Performance Measures for Local Agency Traffic Signals

By

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Purdue University
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Abstract

The project focused on accelerating implementation of research recommendations emerging from traffic signal research projects conducted by the National Cooperative Research Program and Indiana Department of Transportation. This project developed specification language that was subsequently used in procurements in Elkhart County, IN; Lafayette, IN; and Morgantown, WV. The performance measures specified in Appendix A and subsequently deployed in Elkhart County, IN, and Lafayette, IN, were the first commercial deployment of real-time traffic signal performance measures recommended by NCHRP 3-79a. The deployment in Lafayette, IN, received an ACEC award in March 2012.

In addition to accelerating implementation, this research project examined the feasibility of deploying adaptive traffic signal control in the near term (next 12-18 months). The authors of this report believe the detection requirements and the level of engineering staff support required to operate the current generation of adaptive control systems do not warrant implementation without careful assessment of detector placement, detection quality, and a commitment by the agency for substantial recurring engineering support to operate those systems. Instead, the authors recommend pursuing a hybrid approach of scheduled review of traffic signal performance measures to identify performance improvement opportunities and the use of the link-pivot algorithm developed by Purdue. Should an agency wish to pursue adaptive control, we strongly recommend both agency and consultants involved in that decision participate in one of USDOT’s webinars most recently entitled “Keeping Risks in Check: Applying the Updated FHWA Model Systems Engineering Document to Adaptive Signal Control Technology Systems (ASCT) Implementation.” These webinars are regularly held, the most recent one conducted on December 20, 2012.
Chapter 1. Introduction

1.1. Report Structure

This is the final report for Indiana LTAP project entitled, “Performance Measures for Local Agency Traffic Signals.” This project began in January 2009 and concluded in December 2012. The project benefited from extensive in-kind vendor support, strong collaboration with Elkhart County and the City of Lafayette, and on-going support from the Indiana LTAP office. The project focused on accelerating implementation of research recommendations emerging from traffic signal research projects conducted by the National Cooperative Highway Research Program and Indiana Department of Transportation.

Chapter 2 provides a background on Traffic Signal Performance Measures emphasizing the importance of performance measures and implementation opportunities.

Chapter 3 explains the importance of high quality vehicle detection for Traffic Signal Performance Measures and summarizes findings that resulted in a recommendation to retrofit existing video detection with thermal cameras to improve the detection quality.

Chapter 4 describes the implementation of Bluetooth probe data collection to evaluate traffic patterns to provide network level information to develop strategic and tactical traffic management plans for special events.

Chapter 5 describes an assessment of the applicability of adaptive control systems for use by local agencies in Indiana. The authors of this report believe the detection requirements and the level of engineering staff support required to operate the current generation of adaptive control systems do not warrant implementation without careful assessment of detector placement, detection quality, and a commitment by the agency for substantial recurring engineering support to operate those systems. Instead, the authors recommend pursuing a hybrid approach of scheduled review of traffic signal performance measures to identify performance improvement opportunities and the use of the link-pivot algorithm developed by Purdue. Should an agency wish to pursue adaptive control, we strongly recommend both agency and consultants involved in that decision participate in one of USDOT’s webinars most recently entitled “Keeping Risks in Check: Applying the Updated FHWA Model Systems Engineering Document to Adaptive Signal Control Technology Systems (ASCT) Implementation.” This webinar can be found at: http://www.pcb.its.dot.gov/t3/s121031_asct_impl.asp. Representatives from FHWA have also visited Indiana in the past year to conduct similar workshops.

Chapter 6 is a forward-looking chapter that demonstrates the opportunities for conducting a central system in the loop (CSIL) evaluation of a proposed signal system. In the near term, this CSIL will be used to demonstrate the Elkhart system to decision makers. In the long term, this is
a model that local agencies could require consultants to demonstrate (and quantify) the benefits of a proposed system prior to proceeding with a large capital procurement.

Chapter 7 provides a summary of the impact this project has had in Indiana and across the country.
1.2. Implementation Partnership Philosophy

The philosophy used in the course of this project was that the most useful and durable products of research involve collaboration between: universities, local agencies, and vendors. Universities provide ideas for new ways of looking at things and work out the best of the new ideas. Agencies provide feedback throughout the project about what would be of the most value to them in their day-to-day operations. Vendors provide the long term support for ideas that are vetted through the university and agency collaboration. This philosophy is shown in Figure 1.

This approach has many benefits. Universities do not develop research tools that are too complex to be implemented or understood by practicing professionals. Vendors get new ideas for products and understand the need and market potential for these products before committing considerable resources for development. Local agencies are provided with tools that are truly useful and are integrated in their existing system framework, and do not require large time commitments for implementation and maintenance.

![Diagram showing the partnership between universities, agencies, vendors, and traffic signal performance measures.]

*Figure 1: Research Philosophy*
Chapter 2. Traffic Signal Performance Measures

2.1. Motivation

The state of signal operations in the US has been documented as very poor, as shown by the National Traffic Signal Report Cards seen in Figure 2. Developing a sustainable framework for implementing traffic signal performance measures was the objective of this research. Starting in the early 2000s, Purdue University had been developing better ways to collect and quantitatively analyze data from traffic signal systems. The guiding principle was that better data needed to be collected, and theoretically sound tools for analyzing that data were required to improve traffic signal operations. Otherwise it is difficult, and often subjective, to determine if signal changes are making a positive impact or not.

![Figure 2: National Traffic Signal Report Cards, 2005, 2007, 2012](image)

To improve traffic signal operations, the focus of Purdue research has been to leverage high-resolution data and use it to create a ‘picture book’ approach to signal management. Simple graphic representations built from quality data can help engineers and technicians to understand how their signals are operating at a glance.

Currently, assessing signal timing changes is difficult, expensive, and time intensive. The traditional means of retiming traffic signals can be seen in Figure 3 and Figure 4. The most difficult part of the current process is the final assessment of the retiming effects. Due to the expense and time required to both gather the data and perform the analysis needed to make an
assessment of retiming efforts, agencies are often unable to do any data driven analysis and rely instead on anecdotal and observational assessments. Developing better tools to accomplish this crucial step was the impetus for the original performance measures research.

---

**Figure 3: Traditional Signal Timing Flow Chart**

**Figure 4: Current Signal Re-timing Work Flow**
2.2. Development

Research at Purdue to collect hi-resolution data and use it in the creation of better signal management tools began field testing in 2003. At that time a second signal cabinet was placed next to the operating cabinet at two INDOT intersections. The second cabinet was hard-wired into all of the inputs and outputs of the operational cabinet, and each electrical impulse, such as vehicle detections, etc., was logged. By 2006, the second cabinet was made obsolete by the new generation of signal controllers, notably the Econolite ASC3.

The new controllers could log all events internally to the nearest tenth of a second. Automated downloads of these log files, and generation of performance measure graphs was developed by 2008. The standard performance measure graphs were converted into contract specifications—by this project—for procurement of central management systems in 2010 (See Appendix A). By early 2011, the first two systems to use these specifications were delivered to the City of Lafayette, Indiana and Elkhart County, Indiana. This development timeline can be seen in Figure 5.

![Figure 5: Evolution of Performance Measures](image)
How the modern implementation of performance measures within a central system works, is shown graphically in Figure 6. The data is collected at individual intersections by the local controller in hi-resolution data files. These data files are then uploaded periodically via FTP to a central database server, where the data is ingested and stored. The central system then runs queries on this stored data to create the performance measure graphs requested by system users.

![Figure 6: Representation of Performance Measure Implementation within a Central System](image)

Although Purdue defined an extensive set of Performance measures in a series of TRB papers and NCHRP reports (4, 5, 7, 8, 9, 13, 14, 15, 18, 21), this research identified a set of seven basic performance measures that would be particularly useful for local agencies to pursue for near term implementation. These performance measures are listed in Table 1 and explained in the following section. Appendix A provides the specification language that can be used by agencies for specifying the functional definition of these performance measures. The specification defined in Appendix A of this technical report stimulated representatives from the three vendors (Siemens, Econolite, and Peek) to have representatives participate in the development of a document that defined a standard set of high resolution data objects (25).
Table 1: List of Standard Performance Measures

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<td>Green Time Plot</td>
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<td>Volume to Capacity Ratio</td>
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<td>Split Failures</td>
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<td>Purdue Coordination Diagram</td>
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<td>Percentage of Phases with Pedestrians</td>
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The cycle length graph, as seen in Figure 7a, covers a time frame of an entire day, plotting the length of each cycle on the y-axis. Vertical lines are also shown on the graph at the time of any timing pattern changes. The report on the actual cycle lengths used by a signal in a time frame is an important performance measure. It allows the engineer to verify that all signals in a coordinated system are operating at the same cycle length during each time of day plan, a requirement for coordination. While it may seem a simple measure, inaccuracies in programming the cycle lengths of coordinated signal systems is a common problem, and has seriously adverse effects on travel time.
The Equivalent Hourly Flow Rate graph contains a section for each of a controller’s standard eight phases. The x-axis covers the entire day, while scatter points are plotted on the y-axis corresponding to the flow rate in vehicles per hour, estimated from the detector calls placed on each approach. This can be seen in Figure 7b.
The Green Time Plot again shows each of the standard eight signal phases, and plots the amount of green time each phase received, during each cycle of the day. This can be seen in Figure 7c.
The Volume to Capacity graph shown in Figure 7d displays the calculated volume to capacity ratio for each cycle of each phase. It also displays the volume to capacity saturation line at 1.0.
The Split Failures graph shows the number of split failures during a defined period that occur on each phase. This can be seen in Figure 7e.

![Figure 7e: Example of Split Failures](image)
The Purdue Coordination Diagram plots multiple data points for each signal cycle on a single graph. These graphs, shown in Figure 7f, cover only a single phase, and plot the time of day that the cycle began along the x-axis, with the time within the cycle plotted on the y-axis. Data points included in each plot are: vehicle arrivals, start of green, start of yellow, and start of red splits. The start of green band, for instance, can be seen as the green line in Figure 7f.

Figure 7f: Example of Purdue Coordination Diagram
The Phases with Pedestrians graph shows the four main phases that would typically have an associated pedestrian phase. The x-axis shows the time of day, while the y-axis displays, as a percentage, the number of signal cycles in a thirty minute period that have a pedestrian activation. Figure 7g shows this graph.

These performance measures have now been implemented in central signal management systems, as seen in Figure 8. In this figure you can see how the conceptual graphics from the original research (shown in Figure 7) has been incorporated into the central system suite of applications. Further example of the transition from the original PCD performance measure to the central system equivalent can be seen in Figure 9.
Figure 8: Example of Performance Measure Report as Part of a Central System

Figure 9: Original PCD Diagram Next to Central System Version
2.3. Implementation

Performance measures within central systems are now available nationwide and have been adopted in Lafayette, IN; Elkhart County, IN; Mishawaka, IN; and Morgantown, WV. The locations of these agencies are illustrated on Figure 10. Each of these agencies has used variations on the functional specification language shown in Appendix A to procure those central systems.

Figure 10: Location of Agencies Adopting Performance Measures
2.3.1. Examples of Performance Measure Implementation in Elkhart County

Elkhart County employs a central management system to manage signals on two corridors: CR17 and CR20. These corridors can be seen in Figure 11. Examples of each of the performance measures used in Elkhart County follow. Detailed descriptions of each of these measures, and how they are constructed, can be found in Appendix A, and in references 4, 5, and 7.

- The cycle length performance measure provides a good tool to ensure cycle lengths of successive signals are matched for each pattern. This can be seen in Figure 12. This figure has the cycle lengths (C) and points of time of day plan changes highlighted. Since this particular intersection is running actuated-coordinated, you can see minor stochastic
variation in the cycle length from cycle to cycle. If that mode was not enabled, the cycle length would not show any stochastic variation cycle to cycle.

Figure 12: Example Cycle Length Performance Measure

- A quick check of the flow rate on each approach to a signal is provided by the flow rate performance measure. This graph is useful in determining the relative importance of each phase, and the efficacy of the start and end times of timing patterns. Figure 13 shows an example of this performance measure.
Figure 13: Example Flow Rate Performance Measure

- The green time performance measure is used to verify that the appropriate green time values have been programmed for a signal. It also provides a record of how much green time was actually used throughout a period, allowing the engineer to fine tune split times if need be. Figure 14 shows an example of this performance measure.
The volume to capacity ratio performance measure is useful in identifying movements that might be experiencing a lack of capacity and require more time, and those that may have extra time to reassign. Figure 15 shows an example of this performance measure.
The split failures performance measure indicates the number of split failures that occur on a phase by time of day. This measure quickly identifies the phases that may require more time during the cycle, as well as those that have adequate time. Figure 16 shows an example of this performance measure.

Figure 15: Example Volume to Capacity Ratio Performance Measure

- Stop bar detection only, no counters, short cycle, gives banding
- Significant difference in phase length
Perhaps the most useful performance measure for coordinated corridors is the Purdue Coordination Diagram (PCD). In Figure 17c) an example from Elkhart County shows the typical randomness of free operation early in the morning, followed by two distinct coordinated patterns through the bulk of the day. The PCD shows the start of green time and red for each cycle of the signal. Individual detector calls, as vehicles approach the intersection, are shown by black dots. You can quickly learn to discern the differences in good or bad coordination by observing where the clusters of black vehicle arrivals fall. The more arrivals between the green and red bands, the better.
During free operation random cycle lengths

a) PCD Showing Random Cycle Lengths
b) PCD Showing Example of Good Vehicle Progression

Good progression: clusters arriving on green
The percentage of phases with pedestrian activations performance measure helps the engineer identify which signals, and which phases therein, have the heaviest pedestrian usage. Phases with significant usage can then be reviewed to ensure there is adequate split timing so that pedestrian activations do not force the signal out of coordination on a regular basis, harming the corridor’s progression. Figure 18 shows examples of this performance measure. This performance measure can also show errors in push button calls to the controller, as can occur when push buttons become stuck.
a) Example Percentage of Phases with Pedestrians Performance Measure

Number of activations in a period, per phase
2.3.2. Implementation Specifics

Implementation of performance measures in a local agency system requires three main elements. The local signal controllers at each intersection have to be a model that is capable of collection high-resolution event data. At the time of this writing, Econolite and Peek have controllers capable of this.

Secondly, the system will need to have an Ethernet based communication system to allow data from the controllers to be uploaded to the central system. This can include radio systems, fiber optics, cell modems, or combinations of each.

Finally, the agency will have to decide on a central system that is capable of using the collected and stored data to produce the performance measure graphics. At the time of this writing Econolite’s central system Centracs is the only system on the market capable of this function.
Costs associated with implementation will vary by the number of signals an agency incorporates, the geographic disbursement of the signals, and the amount and type of existing communications infrastructure that is in place. Upgrading signal cabinets with new controllers and communications gear generally costs $5,000 to $15,000. Cell modems can be purchased for less than $800 and government rate data plans are approximately $30 per month. The Elkhart system was funded using Congestion Mitigation and Air Quality (CMAQ) funds. Upgrades to systems to improve coordination are generally eligible for federal aid, allowing local agencies to leverage local funds to put performance measures in place.
Chapter 3. Evaluation of Thermal Sensors for Vehicle Detection

3.1. Background

As was seen in Chapter 2, detecting demand (vehicles or pedestrians) is a critical input to virtually all performance measures. Loop detectors have traditionally been used to provide vehicle detection. However, non-intrusive detection technologies, such as video detection are attractive, particularly when pavement condition is challenging, as seen in Figure 19.

![Figure 19: Example of Deteriorated Pavement Condition](image)

Video detection systems, in which category thermal systems broadly fall, have established performance difficulties, particularly at night and in inclement weather (1,2,3). This has made their implementation (notably by the Indiana Department of Transportation) somewhat limited.

Because of INDOT’s moratorium on video detection, the only video detection in the state is at local public agency operated signals. Video detection was the standard for signals at Elkhart
County up until 2009. As can be seen in Figure 20, the majority of signals maintained by the County use video detection for stop bar detection. This situation is not unique to Elkhart County, and given that the cost of rebuilding intersections to use loop detection is very costly, it is important to local agencies to identify options that will allow them to manage their systems in the most cost effective manner possible.

![Image of Elkhart County Signals, with Video Detection Systems Shown By Purple Pushpins](image)

**Figure 20: Elkhart County Signals, with Video Detection Systems Shown By Purple Pushpins**

Thermal image sensors for stop bar presence detection have recently been introduced to the traffic industry as an alternative to traditional video cameras. The promise of this new application of thermal technology is to retain the benefits of video systems (flexible and less intrusive) while mitigating the performance challenges (nighttime headlight glare effects, and loss of detection during inclement weather). Replacing aging video cameras with thermal sensors has also been identified as a possible cost effective management option: improve detection without extensive reconstruction of the intersection.

Due to the recent arrival of thermal cameras in the traffic market there has been limited quantitative performance analysis to date of their on-street performance. Early deployments have tended to have anecdotal reports of solving specific problems, such as daily periods of shadows.
or solar glare. It is hypothesized that benefits of thermal image sensors include: less sensitive to most forms of precipitation (depending on wavelength used), no need for lighting, no effect on operation from headlight glare, reduced need to clean lenses, and reduced effects of direct sunlight on performance.

Examples of video and thermal images are shown for day and night conditions in Figure 21. As part of this project a quantitative assessment of the technical benefits of thermal systems was conducted.

![Figure 21: Daytime And Nighttime Images From Thermal Sensors Compared to Video](image)

The evaluation concluded that the thermal sensors generally performed better than video detection, especially during night time operations. Their accuracy, though not at the level of loop detectors, was considered adequate for traffic operations, with few missed or false call errors of any significant length (see Appendix B, Table 1). Perhaps of greater significance was the nearly complete removal of call activation and termination time bias in day vs. night operation. This bias, a known issue for video systems, results in losses of efficiency and makes appropriate extension timing difficult.

The complete paper, accepted by the Transportation Research Board for publication, is contained in Appendix B.
3.2. Implementation

The direct applicability of this research to local agencies, and its ready-for-implementation status, is shown in that Elkhart County has begun using thermal sensors as their standard replacement equipment for video cameras based on the results of the test. The models used by the County connect with little additional configuration to the existing camera wiring. Figure 22 shows the locations that are now using thermal sensors for stop bar detection. The County has placed 10 thermal sensors in operation since the completion of the research study. As word of this quantitative evaluation of thermal cameras in Elkhart County has spread, copies of the paper shown in Appendix B have been distributed widely across the United States and as far away as New Zealand.

![Figure 22: Elkhart County Signal Locations Using Thermal Sensors, Shown by Violet Pushpins](image-url)
Chapter 4. Bluetooth Data Collection

4.1. Background

Special events such as local fairs present particularly challenging traffic conditions for local agencies to develop traffic management plans for because there is little quantitative data regarding Origin-Destination (O-D) traffic patterns and delay for those O-D pairs. In the last ten years, the collection of anonymous Bluetooth device MAC addresses (unique device identification numbers) have been used in a number of transportation related studies (6,11,12,22). Bluetooth collection in transportation has gone from an element for researchers only, to fully developed commercial deployments in this time.

Bluetooth collection is used predominately for two types of studies: travel time, and Origin-Destination. This project used Bluetooth for both types of studies at various times. During corridor analysis periods, travel time was collected in the test section to use as an effectiveness metric. Changes in timing plan parameters could be compared to changes in travel times through the section, as well as to performance measures such as PCDs, to assess the usefulness of the changes.

In O-D studies, two or more Bluetooth collection stations are set up along travel paths of interest. By matching which devices passed by various stations, an idea of where travelers began and ended their trip, as well as the intermediate path they used, can be developed.

This discussion of Bluetooth data systems and the following case study is being presented to demonstrate for local agencies how Bluetooth may be used to solve certain problems. Seeing a representative study, and the types of results that can be obtained, should help agencies in developing a scope of work for a consultant-performed study.

4.2. Implementation

An example of the use of Bluetooth collection of particular note during this project was for the Elkhart County Fair in July 2012. The Elkhart County Fair, in Goshen, Indiana, is one of the largest fairs in the country, with over 200,000 visitors.
At the request of the fair board, the Elkhart County Highway Department deployed a number of traffic monitoring devices (Figure 23) during the fair period, including nine Bluetooth collection cases (Figure 24 and Figure 25).
The O-D parings for fair traffic, determined from the Bluetooth devices, allowed the directional split of traffic to be determined. Understanding the routes travelers use to access the fairgrounds can help identify appropriate traffic management plans (of which signal timing plans are important) and identifying areas needing more attention (i.e. police control, directional signage, etc.). The determined directional split of fair traffic can be seen in Figure 26.
Travel times were also determined from the collected Bluetooth data and compared to the traffic counts along the main feeder roads. Operational problems were then identified, showing when flow reached saturation and travel times rose. This can be seen in Figure 27. The peak hours inbound and outbound were also identified from this information.

The O-D and travel time information collected was used by the Highway Department to make a set of recommendations to the fair board to improve future traffic access to the fairgrounds.
Figure 27: Travel Time Analysis vs. Traffic Flow for Main Approach to Fair Grounds

Traffic backups shown as reduction in flow and increase in travel time.
Chapter 5. Adaptive/Active Signal Systems and Algorithms

5.1. Objective

Adaptive signal systems and algorithms are an area that has been receiving increased attention over the past few years. The Federal Highway Administration has identified this as a focus area, and has been making a coordinated effort to promote the concepts of well managed signalized corridors, including the use of adaptive signal systems.

Adaptive signal systems use analysis of real traffic (typically by a function of detector calls or occupancy) to improve signal operations. These improvements often include changing offsets to improve progression on coordinated systems, and changing the phase split timings at individual intersections. ‘Active’ systems imply that these adaptations are occurring in real-time by an ongoing process in the central system. ‘Adaptive’ generally includes both active systems and those that use relatively recent traffic patterns to determine improved operational plans to be implemented in a preemptive mode.

Based on this new emphasis, this project sought to implement some of the adaptive/active signal systems currently receiving the most attention in a real-world setting. The objective was to both quantify the potential benefits of these systems to local agencies, as well as gather implementation experience.

5.2. Project Testing

The project identified one adaptive signal system and one active traffic management algorithm to evaluate. The active traffic management algorithm evaluated was the link-pivot algorithm, which uses hi-resolution data collected from the signal system (the same data used to generate the performance measures of Chapter 2) to progressively calculate the optimum offset time of each signal in a system, and then project that offset change back to any upstream signals. The entire system is thereby optimized in a step-wise manner.

To test this algorithm, the test section of five signals on Elkhart County’s County Road 17 Corridor, was first analyzed and nominally optimized with the commercial program Synchro.
Synchro produced recommendations for both cycle lengths, splits, and offsets. These recommendations were then programmed into the active timing patterns and the system was operated with them for a period of a week while the travel times and hi-resolution data was collected.

Based on this first week of operation, the link-pivot algorithm was used to calculate offsets that would create improved percentage arrivals on green. The operational signal timing plans were then revised to reflect these new offsets and the system was run for another full week of data collection. This was repeated twice more, resulting in three successive link-pivot improved plans after the initial Synchro week.

The intention was to then implement the ACS Lite adaptive system on the base Synchro timing plans and compare it to the link-pivot algorithm plans.

### 5.3. Findings

The link-pivot algorithm was found to improve operations (versus the Synchro timing plans), moving the arrivals on green from 85.5% to 87.1% for the AM pattern, 82.3% to 82.7% for the Midday pattern, and 80.1% to 81.4% for the PM pattern. Furthermore, the average travel time was reduced by 3.0% for northbound traffic and 5.8% for southbound traffic.

While this implementation of link-pivot was conducted outside of the central signal management system, a CE 565 class project has integrated this into the Centracs central system software and dialog with the vendor is underway to integrate this into their core product (much like the Purdue Performance Measures have been integrated).

The project objective of comparing link-pivot to Synchro and ACS Lite timings was not able to be completed. In the course of setting up ACS Lite on Elkhart County’s Centracs system it was determined that the use of video detection and the location of those detection zones precluded a successful deployment of ACS-Lite.

Like all adaptive systems, ACS Lite is dependent on accurate vehicle detection within the system to operate. The recommended placement and configuration of detectors to operate ACS Lite was not consistent with standard Indiana Department of Transportation (INDOT) signal design practice in Indiana. The majority of local agency signals in the state follow the INDOT standards, even when federal or state funding was not involved in their construction.
The use of performance measures to systematically review signal operations on a regular schedule, and identify potential problem areas, coupled with using the link-pivot algorithm to optimize coordinated patterns, appears to be a more realistic, attainable method of improving signal operations. Adaptive/active systems first identify if a problem exists, and if so they then gradually adjust system timings to compensate for the problem. Normal settings used often require several minutes of a problem to be present (such as high detector occupancy) before the adaptive/active system acts. The system then varies the offset (for instance) a few seconds in each cycle. With common cycle lengths on the order of one and a half to two minutes, it can take an appreciable amount of time before the ‘improved’ timing is fully implemented. By the time the new timing plan is implemented the original triggering event has subsided. For instance, high traffic volumes during a 15-minute period would be over before an adaptive/active system could fully revise the timing plans. The system would then spend an equal amount of adjustment time returning to the normal timing plan.

Using the performance measure tools described in Chapter 2 allows for the creation of better timing plans, based on historic data. Traffic flow typically follows the same diurnal patterns. Performance measures allow engineers to see these patterns and anticipate them. If there is always a peak in traffic at 7:45 AM, a plan can already be programmed and ready for it, versus waiting for it to happen first and then reacting to it. The link-pivot algorithm can then fine tune the pattern for coordinated systems, beyond what an engineer can ‘see’ in the performance measure graphics. This hybrid approach appears to hold the better potential for improving the state of signal timing practice by local agencies. There is little complex set-up required, nor a need for staff with advanced technical skills.

The use of the link-pivot algorithm will be useful for coordinated signal systems with three or more signals. The level of time needed to analyze systems with three or 30 signals is about the same level of effort, once it is initially configured. Implementing the recommended changes will take an amount of time relative to the total number of signals and signal plans that have timings revised, as each optimized plan will require editing of the controller’s database. Optimizing timings with the link-pivot algorithm may initially be a weekly operation, but will probably become more of a monthly task once the operations approach optimal. Implementing updates may then take on the order of a few hours to a day a month for a technician, depending on system size. Training needed to use the link-pivot algorithm is minimal once the analysis spreadsheet is configured and its use is understood by the agency. After this, changes are made to timing plans using the standard controller database editor.
However, technology continues to evolve and these recommendations may warrant revisiting in another 12-18 months as technology matures. Should an agency wish to pursue adaptive control, we strongly recommend both agency and consultants involved in that decision participate in one of USDOT’s webinars most recently entitled “Keeping Risks in Check: Applying the Updated FHWA Model Systems Engineering Document to Adaptive Signal Control Technology Systems (ASCT) Implementation.” This webinar can be seen at:
Chapter 6. Central System in the Loop

6.1. Background

Central System in the Loop refers to using a central traffic signal management application linked directly to a micro-simulation program. Vehicle detections recorded in the micro-simulation are fed into the virtual signal controller, and thereby the central system. The central system can then act on these simulated vehicles as it would real vehicles. Performance measures can be generated for the virtual system—just like a real system—and adaptive systems can simulate real-time timing changes for the virtual controllers. This is the ‘in the Loop’ referred to in the title.

6.2. Project Testing

As part of this project, a Vissim micro-simulation model of the Elkhart County CR17 test section (as described in Chapter 5) was constructed. Each traffic signal in the test section was recreated in the model, with the same detector mappings and placement as the real ones. The actual timing plans in use on the corridor were then implemented on the model controllers. Traffic direction splits, and inbound traffic were based on actual field measurements. A view of the constructed model can be seen in Figure 28.

Once this model was created, the simulation was run and data on travel times and delay were collected. The captured model travel times were then compared to the actual travel times collected on the real test section with Bluetooth devices.
6.3. Findings

As a test scenario, the constructed model was used to recreate the real-world testing of the Synchro and link-pivot timings described in Chapter 5. The Synchro timings were run first, then the final link-pivot timings. These findings were then compared to the actual data collected during the previous test. The modeled timing plan offsets for each scenario can be seen in Figure 29.
The modeled travel time results were generally close to the real-world results measured by Bluetooth collection, with the average travel time varying not more than 15%. Graphs of the cumulative frequency plots for both the northbound and southbound travel times can be seen in Figure 30 and Figure 31 respectively. The Bluetooth lines shown in each graph show the actual measured travel times for comparison to the modeled travel times labeled as Vissim-Synchro and Vissim-Link Pivot.
Figure 30: Comparison of Modeled versus Measured Northbound Travel Times

Figure 31: Comparison of Modeled versus Measured Southbound Travel Times
6.4. Measured vs. Modeled Data

Testing proposed timing changes in this way allows the agency to identify potential problems in settings and configuration before impacting the public. Multiple scenarios can also be evaluated in a relatively short time frame, and the best of these can then be selected for real world implementation.

While modeled results did not exactly match the measured data, the observed data generally performed better than the model. It was also seen that the link-pivot algorithm performed better with real data, than with modeled data.
Chapter 7. Conclusion and Summary of Impact

The Purdue Traffic Engineering Lab team is actively engaged in many state and national research projects related to traffic signal performance measures and active traffic management. As discussed earlier in this document (Figure 1), the research team views strong engagement with agencies and vendors as an important component of moving research into practice. This project focused on identifying opportunities to leverage ongoing state and national research to accelerate implementation at a local agency level.

For example during the evaluation and testing of emerging traffic signal performance measures, the research team for this project identified six performance measures that demonstrated considerable promise, but that were not commercially available. During this research the graphical form of the measures was tested and refined, and sample contract specifications to allow local agencies to acquire them were written. Based on these specifications, the City of Lafayette and Elkhart County were able to procure central signal management systems that incorporated these newly developed performance measures. In fact, the City of Lafayette was recently recognized by ACEC for the deployment of their central system that incorporated traffic signal performance measures (Figure 32). Subsequently, these performance measures are now an available module in the system, and can be purchased by any agency nationwide. Morgantown, WV, (23) and the City of Mishawaka, IN, have purchased the module since it became a standard commercial product. To use performance measures an agency needs: modern signal controllers capable of high-resolution data logging, Ethernet-based communications with field controllers, and a central system for collecting and managing the data.

Vehicle detection performance measures were used to evaluate emerging thermal and video technology for use at traffic signals. It was determined that the state of practice of video detection has noticeably improved in the last decade. Thermal sensors, using off-the-shelf video processing systems, were shown to operate at an acceptable performance level. They were also shown to address some of the known issues with previous video systems, namely: reduced performance in inclement weather, day/night activation/termination time bias, and sun and shadow effects. Local agencies operate most of the video detection systems in the state and finding an improved replacement for aging cameras is likely to be of interest to them. A Transportation Research Board paper was presented at the 2012 Annual Meeting on this research and has received some amount of interest from both local agencies and vendors and is scheduled...
for publication later this year (24). Request for copies of this paper continue to come in and as recently as Dec 1, 2012, a request for a copy of the pre-print version of the paper was received from Auckland, NZ.

Bluetooth data collection was also incorporated at Elkhart County during this project. This system has become a fairly standard technique with many agencies and consultants using a variety of commercially available collection equipment. Bluetooth was used on this project to primarily evaluate travel times on the CR17 corridor, as a corroborating element for the performance measures implemented via the central management system. Bluetooth was also used for a special project conducted for the 2012 Elkhart County Fair where origin-destination, as well as travel time, data was gathered to aid the Fair in improving access to Indiana’s largest County Fair (Figure 26).

Adaptive signal systems that evaluate traffic demand and adjust either signal offsets, cycle split values, or both, have seen heightened interest in recent years. As part of this project, a commercially available implementation of ACS Lite was intended to be evaluated and compared to timings provided by standard engineering software and a link-pivot system of improving corridor travel times (19). In the course of implementing ACS Lite, it was seen that the initial configuration and preparation involved to bring the system on-line required large amounts of time and a high level of technical abilities. The system was also not readily adaptable to real-world situations where detection was not ideal. Even detectors placed per INDOT standards would not be considered ideal to operate the system. It is our opinion that few local agencies would have staff that would either have the time, or the technical training, to successfully implement and operate an ACS-Lite system. In contrast, the link-pivot algorithm has shown promise and has been shown to reduce aggregate travel times through the test corridor by a few percentage points over the optimized model produced by commercial evaluation software.

However, technology continues to evolve and these recommendations may warrant revisiting in another 12-18 months as technology matures. Should an agency wish to pursue adaptive control, we strongly recommend both agency and consultants involved in that decision participate in one of USDOT’s webinars most recently entitled “Keeping Risks in Check: Applying the Updated FHWA Model Systems Engineering Document to Adaptive Signal Control Technology Systems (ASCT) Implementation.” This webinar can be seen at: http://www.pcb.its.dot.gov/t3/s121031_asct_impl.asp

The use of a traffic micro-simulator linked to the central system (central system in the loop) is beginning to show promise, and is the current focus of future work. This system allows the
agency to implement new timing plans on one, or a corridor, of virtual signals, and thereby evaluate the potential of changes before using them on the real traffic signals. Configuration problems can be detected before disrupting the traveling public, and multiple scenarios can be evaluated in a matter of hours versus weeks for real-world implementations. Furthermore, and perhaps of more significance, this central system in the loop evaluation technique could be specified by a local agency for a consultant to perform to support their recommendation for procuring a central system or adaptive system.

Figure 32: Jenny Miller (City of Lafayette), Fred Koning (City of Lafayette), and Tom Vandenberg (BFS) Receiving ACEC Award on March 3, 2012
References


Appendix A. Procurement Specification for Performance Measures
TRAFFIC SIGNAL PERFORMANCE MEASURES

Description. This work shall consist of providing software tools within the Traffic Management Center (TMC) Management System Software to analyze performance measures, from data recorded by the traffic signal controllers, and provide graphical representations of these measures.

1. General
   a. The required performance measures shall be available, by user selection, for any intersection within the monitoring system.
   b. The date of the performance measure plot shall be user selectable from all available dates in the data set.
   c. In performance measures where only one phase of an intersection is plotted, the phase plotted shall be user selectable from all available.
   d. All performance measures shall be capable of plotting to postscript system printers and also capable of exporting as pdf files with appropriate headers, footers, and legends in a variety of sizes including 8.5x11 in. and 11x17 in.
   e. Control of the performance measure functions shall be via a Graphical User Interface window or field within the Management System Software.
   f. The system shall be capable of browsing to, and calculating performance measures on data sets kept on both networked database servers, and on user loaded archive data files.

2. Required Performance Measures
   a. Controller Cycle Length Plot
      i. X axis showing time of day for a 24 hour period running from 0 hrs (midnight) to 24 hours of the same selected day.
      ii. Y axis showing the cycle length in seconds, with 0 at the origin.
      iii. Plot of each cycle length run by the controller during the day, in chronological order,
      iv. The user can select the option of either plotting discrete cycle lengths each cycle as points, or with a continuous line between data points.
   b. Equivalent Hourly Flow Rate Plot
      i. Figure divided into eight areas, one for each phase of a standard eight-phase controller. Phases 1-4 plotted on the top row, phases 6-8 plotted on the bottom row. Phase number listed in each area with associated user defined lane movement descriptor (N, NL, S, SL, etc.).
      ii. X axis of each area showing time of day from 0 to 24 hours.
      iii. Y axis of each area showing equivalent hourly vehicle volume in vehicles/hour, and running from 0 to user selectable maximum (default to 1500) from bottom to top of axis.
      iv. Scatter point plot of the equivalent hourly flow rate, aggregated for each 15 minute period of the day, for each phase.
      v. Line plot showing for each phase a moving average of the data points in the above section. The moving average window shall be user definable, but default to a 20pt moving average.
      vi. Vertical lines through each area, full height, indicating the time of each controller pattern change (e.g. AM to Midday pattern change). These vertical lines shall be a different color than the data points and moving average lines.
   c. Green Time Plot
      i. Figure divided into eight areas, one for each phase of a standard eight-phase controller. Phases 1-4 plotted on the top row, phases 6-8 plotted on the bottom row. Phase number listed in each area with associated user defined lane movement descriptor (N, NL, S, SL, etc.).
movement descriptor (N, NL, S, SL, etc.).

ii. X axis of each area showing time of day from 0 to 24 hours.

iii. Y axis of each area showing the green time in seconds, and running from 0 to maximum green time recorded on any of the eight phases, from bottom to top of axis.

iv. Scatter point plot of the actual green time for each cycle through the day, for each phase.

v. Vertical lines through each area, full height, showing the time of each controller pattern change (e.g. AM to Midday pattern change). These vertical lines shall be a different color than the data points.

d. Volume to Capacity Ratio Plot

i. Figure divided into eight areas, one for each phase of a standard eight-phase controller. Phases 1-4 plotted on the top row, phases 6-8 plotted on the bottom row. Phase number listed in each area with associated user defined lane movement descriptor (N, NL, S, SL, etc.).

ii. X axis of each area showing time of day from 0 to 24 hours.

iii. Y axis of each area showing the Volume to Capacity ratio for that phase, and running from 0 to 1.5 from bottom to top of axis.

iv. Scatter point plot of the actual volume to capacity ratio, aggregated for each 15 minute period of the day, for each area.

v. Line plot showing for each phase the moving average of the data points in the above section. The moving average window shall be user definable, but default to a 20pt moving average.

vi. Vertical lines through each area, full height, showing the time of each controller pattern change (e.g. AM to Midday pattern change). These vertical lines shall be a different color than the data points and moving average line plot.

vii. Horizontal line, full width of each area, at the volume to capacity ratio of 1.0. May be same color as vertical lines specified above, but shall be a different color than the data points and moving average line plot.

e. Number of Split Failures per Half Hour Bin Plot

i. Figure divided into eight areas, one for each phase of a standard eight-phase controller. Phases 1-4 plotted on the top row, phases 6-8 plotted on the bottom row. Phase number listed in each area with associated user defined lane movement descriptor (N, NL, S, SL, etc.).

ii. X axis of each area showing time of day from 0 to 24 hours.

iii. Y axis of each area showing time of day from 0 to 24 hours.

iv. Scatter point plot of the actual green time for each cycle through the day, for each phase.

v. Vertical lines through each area, full height, showing the time of each controller pattern change (e.g. AM to Midday pattern change). These vertical lines shall be a different color than the data points.

vii. Horizontal line, full width of each area, at the volume to capacity ratio of 1.0. May be same color as vertical lines specified above, but shall be a different color than the data points and moving average line plot.

f. Coordination Diagram Plot

i. Single plot area showing a selected phase.

ii. X axis showing time of day from 0 to 24 hours.

iii. Y axis showing time in cycle in seconds, and running from 0 to the maximum cycle length for the day, from bottom to top of axis. 0 on the Y axis equates to the start of red for the selected phase.

iv. Green line plot of the start of the green indication for each cycle. X coordinate of
each data point connected by green line is the time that specific cycle started (referenced to the beginning of the cycle, i.e. the beginning of red). Y coordinate of each data point connected by green line is the time (in seconds) that the phase received the green indication after the beginning of red for that cycle.

v. Yellow line plot of the start of the yellow indication for each cycle. X and Y coordinates of each data point on yellow line calculated similarly as green line points.

vi. Black line plot of the end of the cycle. X coordinates of each data point on black line calculated similarly as green line X points. Y coordinate equal to the time, in seconds, the yellow indication ended and the next cycle started.

vii. Scatter point plot of each recorded vehicle arrival. X coordinate of each data point is the time the cycle started during which the vehicle arrived. Y coordinate equal to the time (in seconds) after the cycle began that the vehicle was detected.

viii. Vertical lines through each area, full height, showing the time of each controller pattern change (e.g. AM to Midday pattern change). These vertical lines shall be a different color than the data points and other lines plotted.

g. Percentage of Phases with Pedestrian Calls Plot

i. Figure divided into four areas, one each for phases 2, 4, 6 and 8 of a standard eight-phase controller. Phases 2 and 4 plotted on the top row, phases 6 and 8 plotted on the bottom row. Phase number listed in each area with associated lane movement descriptor (N, S, etc.).

ii. X axis of each area showing time of day from 0 to 24 hours.

iii. Y axis of each area showing the percentage of cycles in that phase that had a pedestrian call, from 0% to 100% from bottom to top of axis.

iv. Bar graph plots one-half hour wide and as high as the percentage of cycles in that half-hour time period that had pedestrian calls, starting at 0% on the Y axis.

Examples of the above referenced performance measures and related published reference works as cited below can be seen at http://web.ics.purdue.edu/~grossmaj/pm/

Detailed references, including the calculation of the performance measures, data file formats, example plots, data sets, and other guidance can be obtained by contacting Professor Darcy Bullock by email at darcy@purdue.edu. Detailed examples of these performance measures can be found in the following references:


Method of Measurement. The Traffic Signal Performance Measures shall be measured as Lump Sum and include a complete software system, as described herein, furnished, installed, and warranted and made fully operational.

Basis of Payment. Payment for the work included in the Traffic Signal Performance Measures shall be included in the Contract Lump Sum payment of the Design/Build.
Appendix B. TRB Paper on Thermal Sensor Evaluation
Evaluation of Thermal Sensor Video Sensors for Stop Bar Detection at Signalized Intersections

by

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Abstract

Thermal image sensors for stop bar presence detection have recently been introduced to the traffic industry as an alternative to cameras sensitive only to the visual spectrum. This new detection technology, from two manufacturers, was evaluated side-by-side with a video detection system. Inductive loops were used for a comparison to identify discrepancies that warranted manual ground truthing of the video images. The video camera and two thermal sensors operated simultaneously over a 24-hour period, and discrepancies in the loop versus thermal or video detection calls was validated from recorded video. No missed call events longer than 10 seconds were observed, and only a modest number of false calls by the test systems. The bias in activation and termination times was also evaluated during day and night operation for each system.

The study found that the median time difference in activating a detection zone was about one second when comparing day and night operation of the detection system with a video camera. This is consistent with past studies that reported nighttime detection challenges due to headlight projections. However, the thermal cameras had virtually no change in the median activation times when day and nighttime operation were compared. This is a very encouraging finding as it suggests that integrating cameras sensitive to the infrared spectrum hold considerable promise for improving the quality of nighttime video detection.
**Introduction**

Thermal image sensors for stop bar presence detection have recently been introduced to the traffic industry as an alternative to cameras sensitive only to the visual spectrum. Due to their recent arrival in the traffic market there has been limited detailed analysis to date of their on-street performance. Early deployments have tended to have anecdotal reports of solving specific problems, such as daily periods of shadows or solar glare. It is hypothesized that benefits of thermal image sensors include: less sensitive to most forms of precipitation (depending on wavelength used), no need for lighting, no effect on operation from headlight glare, reduced need to clean lenses, and reduced effects of direct sunlight on performance. This paper provides a quantitative assessment of the technical benefits of thermal systems and market forces will ultimately determine what price premium thermal cameras are worth. An example of video and thermal images of a vehicle in westbound lane A are shown for day and night conditions in Figure 1.

**Motivation**

While thermal detection sensors are relatively new in transportation applications, their initial deployments are done by using traditional video detection platforms and just replacing the visual spectrum cameras with thermal cameras. There is a rich body of literature that describes testing protocols and evaluation metrics for video detection systems that can be readily adapted for evaluating these new hybrid systems [1,3,4,6,8,10,11,15,18,19,20,21,24].

The evaluation of thermal sensors conducted in this study builds upon several previous evaluations of video detection technology [1,3,8]. Video detection research dealing with environmental conditions such as rain, snow and wind [16,20,21] are not expected to pose as great a concern for thermal systems, but further work validating those concerns warrant further research beyond the scope of this paper. However, rapid changes in temperature may have effects on thermal systems.

One of the larger challenges reported with video systems has been change in detection zone size between daytime operation when vehicles are detected and nighttime operation when the projection of the headlights is detected [3,17,19]. Thermal sensors are hypothesized to provide much more consistent detection zone sizes during day and nighttime operation. A second area that thermal sensors are hypothesized to provide more robust performance is during periods with substantial shadows projecting into adjacent lanes.

**Literature Review**

A number of transportation agencies have reported on the accuracy and efficiency of video systems [5,9,11,12,14] and the state of Indiana has developed a formal procedure of image system acceptance [7] based on a stochastic review of detector performance and how it relates to signal efficiency [2].

Although a bit of a generalization, the test protocol posted by Indiana proposes four broad classes of performance metrics:

- Number of missed detections greater than a prescribed threshold.
- Number of false detections greater than a prescribed threshold.
- Statistical bias and dispersion of detection zone activation point relative to the intended start of a detection zone.
- Statistical bias and dispersion of detection zone de-activation point relative to the intended end of a detection zone.

The procedure and nomenclature of evaluating video detection system missed and false call errors was proposed by Grenard, et al., [8] and used in later studies [1,3], this used the ‘LxVx’ error type descriptions. In the Grenard et al. approach, detector errors fall into two main categories: loop on, detector off (denoted as L1V0) and loop off, detector on (denoted as L0V1). Figure 2 graphically illustrates L0V1 and L1V0 errors on a short event time-trace diagram. Performance measures have been proposed that define thresholds for quantifying the number and duration of the long duration L0V1 and L1V0 events [2, 7].

There are two other possible errors—loop and detectors both off when a vehicle is present, and both on when a vehicle is not present. These later types of errors, while possible, appear rarely if at all in the test data and are not considered significant. While this study focused on thermal detection—though a video system was also present—the use of the ‘V’ in the error nomenclature (i.e. L1V0) was retained to be consistent with the past research in this area, despite the thermal sensors not technically being video cameras in the visible spectrum. Video output from the thermal sensor to the processing unit was still the basis for the system to determine vehicle detection calls.

The procedure and nomenclature of evaluating video detection system statistical bias and dispersion was proposed by Rhodes, et al. [3] and subsequently extended by others [2,7]. This study followed a similar protocol and developed statistical methods to quantify the short duration L0V1 and L1V0 errors that corresponded to small activation and termination bias and stochastic variation.

**Test Site and Infrastructure**

The evaluation site for this study was at the intersection of County Road 10 and County Road 15 in Elkhart County, Indiana. County Road 10 carries over 14,000 vehicles per day (vpd) and CR15 carries over 900 vpd. The signal system was installed in 2009 and uses inductive loops as its primary form of vehicle detection, both for stop bar presence and advanced detection. The loop detection layout is in accordance with standard Indiana Department of Transportation (INDOT) practice, using four six-foot loops at 15 foot on center spacing for a nominal detection area of 51 feet.

The intersection’s east and westbound approaches (CR 10) have two through lanes and one left turn lane. The north and southbound approaches (CR 15) have a single through lane with one left turn as can be seen in Figure 3.

The three systems evaluated were: Autoscope video, Wireless Technology Inc. (WTI) C-Max Ultra Series thermal sensor, and a FLIR Systems Inc. (FLIR) SR-334T thermal sensor. Both thermal sensors were uncooled vanadium oxide micro-bolometer sensors operating at the 7.5 to 15.5 micrometer wavelengths with resolutions of 320x240 pixels and 30 fps NTSC video output. These cameras and sensors were installed on the westbound and northbound approaches, with the
three types of devices mounted side by side on the luminaire arm, approximately 25 feet (7.6m) above grade (Figure 4).

Each of the cameras and sensors sent raw video via coaxial cable to the processing unit in the signal cabinet. None of these devices had on-board processing and no control communications to them were present.

The detector calls were made by the processing units and logged to the database on the signal controller. Output video feeds showing the detection zone layout and detector call status for each approach and device was sent to a video encoder and saved to a hard drive mounted in the cabinet to be used for verification of results.

A 24-hour period was used for the final test after initial testing and verification of the hardware and software configuration. Each detector’s performance for each of five lanes on the two test approaches was evaluated. For each potential error larger than 10 seconds, human verification was made using the recorded video.

**L0V1 and L1V0 Test Methodology**

To evaluate the effectiveness of thermal sensor systems, this study chose to compare these systems to inductive loop detectors placed in what is a standard layout for stop bar detection in the state of Indiana. Inductive loop detectors are a mature and understood technology within the traffic signal community, and are the predominant technology within the state of Indiana for stop bar presence detection. Previous studies of video technology also used loops as the basis of comparison [1,3].

For this study, the detection calls placed by the thermal sensor systems were compared to calls placed by the loop systems. Of the two main types of errors (L1V0 and L0V1), it has been suggested by Rhodes [1] that the L1V0 is a more significant error. In this case, the loop detects the presence of a vehicle, but the evaluation system does not detect it. This type of error may eventually lead a frustrated driver to ignore the signal indication and proceed illegally, an obvious safety concern. The L0V1 error where the evaluation system makes a false detector call is generally more an issue of inefficiency in the signal cycle, but is not a safety concern. A graphic illustration of these detection error types can be seen in Figure 2.

In the case of both loop and thermal detection, the actual call placed is part of a system. For loops, the system includes the inductive roadway loop, lead-in, and amplifier. In the case of thermal detection the system includes the thermal sensor mounted on the luminaire arm, video cabling, and video processor. For this study, the video processing was carried out by units mounted in card racks within the signal cabinet.

A traditional video detection camera and two types of thermal sensor systems (WTI and FLIR) were evaluated in this study, all using the same in-cabinet devices to process the raw images and determine vehicle calls. Being a more mature product, the video detection camera coupled with the processing unit was a better understood system, with many recommended system variables supplied by the manufacturer. In the case of thermal sensors, there is still little information available about recommended settings for optimal performance. As more of these systems are
deployed, better information regarding optimal settings is likely to emerge. In all cases, however, the evaluation was based on the total system. It was not possible to evaluate, for instance, just the raw images supplied from the sensors to each other. The system approach should also better characterize the experience that an agency that adopts these sensors might expect.

Detector on/off calls were logged to the high resolution data collector built into the signal controller [22]. Each call is time stamped and also contains the detector number and information on the type of call. These controller data files were subsequently brought into a central SQL database for long term storage and analysis.

**Example Errors**

Figure 5 shows an example of a vehicle detection missed by the WTI thermal sensor for 20.3 seconds. The horizontal axis of Figure 5a corresponds to the time an L1V0 error occurred and the vertical axis corresponds to the duration of the L1V0 error. The 20.3 second false call error is of the L1V0 type, during which time the WTI thermal sensor records no call. Figures f and g show the video recorded at the beginning and end of the error event, verifying that this was a true error of the detector system.

An example of a false call by the video system can be seen in Figure 6. Figure 6a shows a 23.4s L0V1 error that began when a vehicle left the westbound left turn lane. The video detection system did not terminate the call for another 23.4 seconds. The two thermal sensors performed appropriately in this instance.

The FLIR thermal sensor also made an L0V1 type error, as can be seen in Figure 7, when a left turning vehicle apparently triggered a call that the system then held for 56.1 seconds. These are all representative examples of the types of errors observed and the method used to verify them.

**Activation and Termination Errors**

When multiple sensors are used to measure the same thing, there is typically statistical bias and variation in how those sensors respond. In the case of a stop bar detector, there will be some bias with regards to which sensors tend to turn on first and there will be some stochastic variation of that bias based upon the color and height of the vehicle (variation due to optics), and perhaps the ferrous content (variation due to loop detectors). In general, loop detection zones are quite crisp and the variation due to the optics is at least an order of magnitude larger than the variation of the loop detector [23], particularly during nighttime operation because of headlight projection [22]. In general the magnitude of this bias is quite small, typically less than 1 second. Figure 8 shows histograms for the activation and termination bias for a 24 hour period on the west bound left turn lane on July 18, 2011, for all three cameras (Video, FLIR Thermal, and WTI Thermal).

**Results**

**False and Missed Calls**

All sensors were tested concurrently for 24 hours on July 18, 2011, side-by-side, to ensure equal traffic and environmental conditions for all devices. Plots of the performance of each sensor, for each lane of the west bound approach, can be seen in Figure 9, Figure 10, and Figure 11. A ten second error threshold was used for analysis, which flags any L1V0 or L0V1 error that lasts longer than this amount of time. All of the sensors performed reasonably well on these approaches, at the ten second error threshold. The left turn lane and thru lane B had the most
errors recorded, likely due to these lanes having more slow traffic (lane B is also the right turn lane). Occlusion of adjacent detection zones by large vehicles, shadows (thermal and visible), headlight glare (visible only) and other error mechanisms are all potential contributors to false calls for each of the video based systems [1,4,5,9,19]. The false calls in the video and thermal systems are attributed to some of the documented challenges associated with video processing systems, as all three detectors rely on video processing in the end to make detector calls.

Table provides summary statistics for each lane and sensor type, giving the total number of errors as well as the total amount of time of the errors that were visually ground truthed. Ground truthing of potential errors consisted of visually verify the error in the recorded video of each event as it was recognized that the loop detection system might also have been the source of the error. Of particular note is that there were no missed calls that had a duration longer than 10 seconds, except for one event on the WBA approach and only a modest number of false calls that were longer than 10 seconds. The FLIR thermal sensors performed somewhat better than the video camera and the WTI thermal sensor in the false call metrics.

Comparison of Day and Night activation and Termination Errors
As was discussed earlier in regards to Figure 8, a histogram of the activation and termination provides another means of performance evaluation. Detections tightly clustered about zero show a well performing sensor. More dispersed detections show higher variation in a sensor’s performance.

An important element of sensor performance is an evaluation of any relative differences in day versus night performance. For this study, based in northern Indiana in July, the period of midnight to 5 AM, and 10 PM to midnight was designated the ‘night’ period. The ‘day’ period was designated as 7 AM to 8 PM. The transitional dawn and dusk periods were excluded because traditional video cameras are transitioning from day to night performance, making error analysis difficult to quantify.

Traditionally, the performance of video technology has been shown to operate differently in night versus day mode, as detailed by Rhodes and others [3,19]. As thermal sensors are at times marketed as replacements for video image systems, the three systems were evaluated in day and night modes to create a comparison for this critical time period.

Figure 12 shows the cumulative frequency distribution (CFD) of the activation bias times for the three lanes and three sensors on the westbound approach. As can be seen in Figure 12, there was a noticeable change in the sensor activation time for the video system between the two periods (Figure 12a,d,g). Earlier night activations are apparent, which is normally attributed to the headlight effect.

The FLIR thermal sensors showed very small differences in operation between the periods (Figure 12b,e,h). Although not quite as small as the FLIR thermal sensor, the WTI thermal sensors showed moderately small differences between day and night operation (Figure 12c, f, i). The northbound lanes were excluded from these results due to the low volumes present, particularly in the night period. T statistically summarizes the difference in operation between day and night operation for activation and termination times. Although t-statistics are provided in
Te, they are probably not robust indicators of performance due to the large difference in volume during the day vs. the night (WBL was 208 vs. 15, WBA was 2925 vs 185, and WBB was 652 vs. 41).

**Conclusions**

Although the study intersection had considerably smaller volumes than previous studies in Indiana [1, 3] and Texas [2], it is one of the most recent video detection studies and suggests the detection technology performance has substantially matured over the past 6 years[1].

However, the most significant finding from this research was the comparison of sensor activation times during day vs. nighttime operation. The very close alignment of the day and night activation times of the FLIR thermal sensor shown in Figure 12b,e,h suggest that these sensors have the potential to substantially improve the operational efficiency of signalized intersections during nighttime operation, a period when traditional video sensors often introduce up to 1 second of additional gap extension time from the headlight projections (Figure 12a, d, g).

One of the details that makes these findings particularly significant is the relative infancy of the integration of thermal cameras with off the shelf detection systems. In comparison to the thermal camera coupled to a detection system, a traditional video camera coupled with the detection system is a more mature product and with better design and configuration guidelines. However, despite this limitation, the preliminary results from this study are very encouraging and suggest that integrating cameras sensitive to the infrared spectrum hold considerable promise for improving the quality of nighttime video detection.

Further work is underway to refine this detection test bed to develop high resolution performance measures that can be compared against those proposed by Indiana [7] and Middleton [2].

**Acknowledgements**

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**References**

12. Middleton, D., and R. Parker. Initial Evaluation of Selected Detectors to Replace Inductive Loops on Freeways. Publication FHWA/TX-00/1439-7-S. Texas Transportation Institute, Texas Department of Transportation, FHWA, College Station, Texas, 1999.
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Table 1: Summary of Observed Errors during 24-Hour Study Period Lasting more than Ten Seconds (July 18, 2011)

a) Summary Of Confirmed Missed Calls From L1V0 Discrepancies >10 Seconds

<table>
<thead>
<tr>
<th>Lane</th>
<th>Video Time</th>
<th>Count</th>
<th>FLIR Thermal Time</th>
<th>Count</th>
<th>WTI Thermal Time</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBL</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>WBA</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10.4s</td>
<td>1</td>
</tr>
<tr>
<td>WBB</td>
<td>0*</td>
<td>0*</td>
<td>0*</td>
<td>0*</td>
<td>0*</td>
<td>0*</td>
</tr>
</tbody>
</table>

* error shown in FIGURE 11 was due to false loop call

b) Summary Of Confirmed False Calls From L0V1 Discrepancies > 10 Seconds

<table>
<thead>
<tr>
<th>Lane</th>
<th>Video Time</th>
<th>Count</th>
<th>FLIR Thermal Time</th>
<th>Count</th>
<th>WTI Thermal Time</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBL</td>
<td>134s</td>
<td>3</td>
<td>47s</td>
<td>1</td>
<td>248s</td>
<td>6</td>
</tr>
<tr>
<td>WBA</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>WBB</td>
<td>29s</td>
<td>2</td>
<td>11s</td>
<td>1</td>
<td>232s</td>
<td>9</td>
</tr>
</tbody>
</table>
Table 2: Mean and Standard Deviation Statistics for Westbound Approach Detection Bias

<table>
<thead>
<tr>
<th></th>
<th>Video</th>
<th>FLIR Thermal</th>
<th>WTI Thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day</td>
<td>Night</td>
<td>Day</td>
</tr>
<tr>
<td>WBL</td>
<td>0.21</td>
<td>0.16</td>
<td>0.35</td>
</tr>
<tr>
<td>WBA</td>
<td>0.43</td>
<td>-0.42</td>
<td>0.29</td>
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<tr>
<td>WBB</td>
<td>0.66</td>
<td>-0.57</td>
<td>0.48</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>0.46</strong></td>
<td><strong>-0.41</strong></td>
<td><strong>0.33</strong></td>
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</table>

<table>
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<tr>
<th></th>
<th>Video</th>
<th>FLIR Thermal</th>
<th>WTI Thermal</th>
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<tbody>
<tr>
<td></td>
<td>Day</td>
<td>Night</td>
<td>Day</td>
</tr>
<tr>
<td>WBL</td>
<td>6.96</td>
<td>0.32</td>
<td>0.52</td>
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<tr>
<td>WBA</td>
<td>0.74</td>
<td>0.42</td>
<td>0.35</td>
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<tr>
<td>WBB</td>
<td>2.49</td>
<td>0.39</td>
<td>2.34</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>1.38</strong></td>
<td><strong>0.41</strong></td>
<td><strong>0.73</strong></td>
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<th>WTI Thermal</th>
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<tr>
<td></td>
<td>Day</td>
<td>Night</td>
<td>Day</td>
</tr>
<tr>
<td>WBL</td>
<td>0.24</td>
<td>0.01</td>
<td>0.40</td>
</tr>
<tr>
<td>WBA</td>
<td>0.52</td>
<td>0.40</td>
<td>0.51</td>
</tr>
<tr>
<td>WBB</td>
<td>-0.07</td>
<td>0.32</td>
<td>0.08</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>0.32</strong></td>
<td><strong>0.35</strong></td>
<td><strong>0.37</strong></td>
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<table>
<thead>
<tr>
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<th>Video</th>
<th>FLIR Thermal</th>
<th>WTI Thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day</td>
<td>Night</td>
<td>Day</td>
</tr>
<tr>
<td>WBL</td>
<td>1.68</td>
<td>0.71</td>
<td>2.47</td>
</tr>
<tr>
<td>WBA</td>
<td>0.30</td>
<td>0.46</td>
<td>0.28</td>
</tr>
<tr>
<td>WBB</td>
<td>1.95</td>
<td>0.49</td>
<td>1.87</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.91</strong></td>
<td><strong>0.49</strong></td>
<td><strong>0.97</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Video</th>
<th>FLIR Thermal</th>
<th>WTI Thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBL</td>
<td>0.09</td>
<td>1.62</td>
<td>1.58</td>
</tr>
<tr>
<td>WBA</td>
<td>25.27</td>
<td>4.26</td>
<td>6.13</td>
</tr>
<tr>
<td>WBB</td>
<td>10.62</td>
<td>5.21</td>
<td>0.97</td>
</tr>
</tbody>
</table>
Figure 1: Daytime and Nighttime Images from Test Sensors
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Figure 5: Missed Call Example At (WTI Sensor)
Figure 6: False Call Example (Video Sensor)

a) WB Left - Loop: Off / Video: On

b) Video correct call

c) Video holds call for 23.4 seconds

d) FLIR correct call

e) FLIR correct no call

f) WTI Correct call

g) WTI correct no call
Figure 7: False Call Example (FLIR Sensor)
Figure 8: Temporal Variation of Activation and Termination for the Westbound Left Turn by Sensor, in Total Number and Percentage of Detections, Where Zero Marks the Activation/Termination of the Loop Detector, Showing Average and Standard Deviation for Activation and Termination Times

a) Video, number of detections
\[ \mu_a = 0.2 \quad \sigma_a = 6.52 \quad \mu_t = 0.18 \quad \sigma_t = 1.56 \]

b) Video, percentage of detections
\[ \mu_a = 0.2 \quad \sigma_a = 6.52 \quad \mu_t = 0.18 \quad \sigma_t = 1.56 \]

c) FLIR, number of detections
\[ \mu_a = 0.37 \quad \sigma_a = 0.5 \quad \mu_t = 0.32 \quad \sigma_t = 2.28 \]

d) FLIR, percentage of detections
\[ \mu_a = 0.37 \quad \sigma_a = 0.5 \quad \mu_t = 0.32 \quad \sigma_t = 2.28 \]

e) WTI, number of detections
\[ \mu_a = 0.80 \quad \sigma_a = 1.05 \quad \mu_t = 0.67 \quad \sigma_t = 4.15 \]

f) WTI, percentage of detections
\[ \mu_a = 0.80 \quad \sigma_a = 1.05 \quad \mu_t = 0.67 \quad \sigma_t = 4.15 \]
Figure 9: Plots for L0V1 and L1V0 Error Types for the Westbound Left Turn Lane Showing Total Duration of Errors in Minutes and Seconds
Figure 10: Plots for L0V1 and L1V0 Error Types for Westbound Thru Lane A, Showing Total Duration of Errors in Minutes and Seconds
Figure 11: Plots for L0V1 and L1V0 Error Types for Westbound Thru Lane B, Showing Total Duration of Errors in Minutes and Seconds
Figure 12: Day versus Night Time of Activation for Each Device Referenced to Loop Activation (Time 0)

a) Video activation time, WBL  
b) FLIR activation time, WBL  
c) WTI activation time, WBL  
d) Video activation time, WBA  
e) FLIR activation time, WBA  
f) WTI activation time, WBA  
g) Video activation time, WBB  
h) FLIR activation time, WBB  
i) WTI activation time, WBB  

---  DAY (0700-2000)  ---  NIGHT (2200-0500) ---