

An Overview and Performance Evaluation of ACS Lite – A Low Cost Adaptive Signal Control System

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ABSTRACT

FHWA recently developed *Adaptive Control Software Lite*, or *ACS Lite*, with the goal of providing a “widely deployable” system that automates monitoring of traffic signal performance and adjustment of signal timing. The *Lite* designation reflects a focus on reducing traditionally high installation and operations costs, which have been the primary impediment limiting the deployment of adaptive systems in the U.S. The system has been integrated and tested with the CORSIM simulation and with signal controllers from four major U.S. manufacturers. This paper provides an overview of the ACS Lite system and the results of independent performance evaluations. Simulation evaluation has demonstrated significant benefits in the context of suboptimal settings, and “no harm done” in the context of signal timing that was optimized with perfect knowledge of the traffic conditions. Field evaluations were then conducted in four cities, with Eagle, Econolite, McCain, and Peek controllers respectively. In comparison with prior field settings, signal timing adjustments by ACS Lite provided substantial reductions in vehicle delay, arterial travel time, vehicle stops, and fuel consumption. The corresponding economic benefits of improved traffic flow were estimated to surpass system deployment costs within the first year.

INTRODUCTION

The Federal Highway Administration (FHWA) initiated development of *Adaptive Control Software Lite*, or *ACS Lite*, to provide a “widely deployable” system that automates monitoring of traffic signal performance and adjustment of signal timing (1). The *Lite* designation reflects a focus on reducing traditionally high installation and operations costs, which have been the primary impediment limiting the deployment of adaptive systems in the U.S. (2, 3).

A series of performance evaluations of the initial ACS Lite research prototype were recently completed, in April 2007. This paper summarizes the project, the resulting system, and the evaluation findings from simulation experiments and four field studies.

BACKGROUND

Growing traffic delays are now ranked as the first or second “largest” community problem by citizens surveyed across the nation (4, 5). Suboptimal signal timing is one contributing factor, attributed with causing an estimated ½ billion person-hours of vehicle delay annually in the United States—a share representing as much as 13% of all traffic delay (6). The state of affairs is poignantly illustrated by Figure 1, the *National Traffic Signal Report Card*, which assesses overall traffic signal operations in the U.S. with a grade of D- (7).

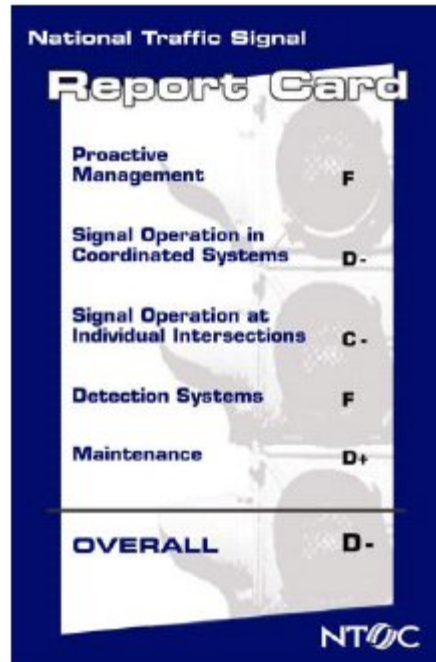


Figure 1. National Traffic Signal Report Card (source: NTOC, 2005).

Off-line signal-timing optimization software, such as Synchro (8), is available to facilitate the task of updating signal timing; and, studies show that the economic benefits of well-timed signals outweigh the costs of retiming by a ratio of 40:1 or more (7). However, the “report card” indicates that timing updates occur with unsatisfactory frequency in actual practice (7).

The National Transportation Operations Coalition (NTOC) generated this report card based on questionnaires collected from 378 agencies across the nation, providing a self-assessment of their signal operations (7). NTOC analysis concludes that agencies are primarily challenged by limited resources—characterized as a “scarcity of funding and staffing” (7). In this environment, daily management has degenerated to “fighting fires”, where the provision of basic traffic control functionality overshadows the provision of efficient operations. This effect is especially pronounced in smaller cities, where traffic signals represent only a small fraction of a city engineer’s responsibilities. Nationally, it is estimated that 75% of signals are in need of retiming (6). These findings suggest the need for on-line tools to automate the retiming of signals.

While it is widely recognized that no single treatment will be the panacea for all traffic delays, adaptive signal timing does have a cross-cutting capability that extends beyond the 13% share of delay attributed to poor signal timing. Adaptive control can automatically reallocate capacity and resynchronize progression for unexpected (i.e., non-recurring) traffic conditions as they occur, flexing the system to accommodate traffic diverting from work zones, crashes, breakdowns, special events, and weather (such as snowed-in, iced-over, or flooded roadway segments).

Intelligent transportation systems such adaptive traffic control have been recognized as a vital ingredient in plans to address the transportation needs of the nation (9, 10). However, agencies in the U.S. have historically been reluctant to adopt adaptive control. Currently, there are approximately 28 adaptive system deployments in the U.S., not including the ACS Lite field sites (11). In 1999, only 8 agencies reported using adaptive control—a level of deployment that prompted the conception of the ACS Lite project (12). A survey of agencies by FHWA has elucidated some of the underlying sources of reluctance (3). Furthermore, feedback has been solicited from practitioners at an international conference, who were invited for a roundtable discussion of adaptive control (2). The feedback from these efforts has provided the following list of concerns that have limited the adoption of adaptive control systems.

- High cost (cited by 70% of responding agencies).
- System complexity.
- Uncertain benefits (cited by 40% of responding agencies).
- Sensitivity to detection.
- Sensitivity to communications.

The objectives of the ACS Lite project—formulated by FHWA—implicitly required directly addressing the concerns listed above. The ACS Lite goals and requirements can be summarized as follows:

- Build a cost-effective, widely deployable adaptive control system.
- Focus on linear, arterial networks.
- Integrate with the CORSIM simulation model.
- Target closed-loop system applications, capable of operating without any central facility.
- Utilize the NTCIP communications protocol, without per-second communications.
- Integrate and field test with all participating NEMA vendors.

The research and development of ACS Lite has been carried out by Siemens, with collaboration and testing support from Purdue University, The University of Arizona, and ITT Industries. FHWA invited signal controller manufacturers that are members from the National Electrical Manufacturers Association (NEMA) to participate in and support the project. The invitation was accepted by Eagle (Siemens), Econolite, McCain, and Peek (Quixote). The project began in 2002, and the last of four field evaluations was completed in 2007.

SYSTEM DESCRIPTION

ACS Lite could be briefly summarized as an adaptive closed-loop system. Figure 2a illustrates a typical closed-loop system architecture, where a supervisory computer monitors and coordinates the timing of several signal controllers. This section summarizes the system architecture of ACS Lite, describing the roles and requirements of the system components—namely, the “local” intersection controllers, their vehicle detectors, and communications.

Architecture Options

The specific configuration of closed-loop systems may vary from one deployment to the next, and ACS Lite is flexible in this regard. This is exemplified in figure 2, which illustrates the system architectures deployed for field tests with each of the four participating manufacturers.

Figures 2a and 2d illustrate that ACS Lite may serve as a replacement for a legacy field master, providing standard features such as clock synchronization and command of patterns according to a time-of-day (TOD) schedule. Conversely, ACS Lite has also been operated in tandem with existing field masters, as shown in figures 2b and 2c, where the existing master maintained pattern control. Furthermore, the ACS Lite software may optionally be hosted on a server at a traffic management center (TMC), as shown in figure 2c; or, the software may run on a field-hardened processor, deployed in the equipment cabinet at one of the arterial intersections.

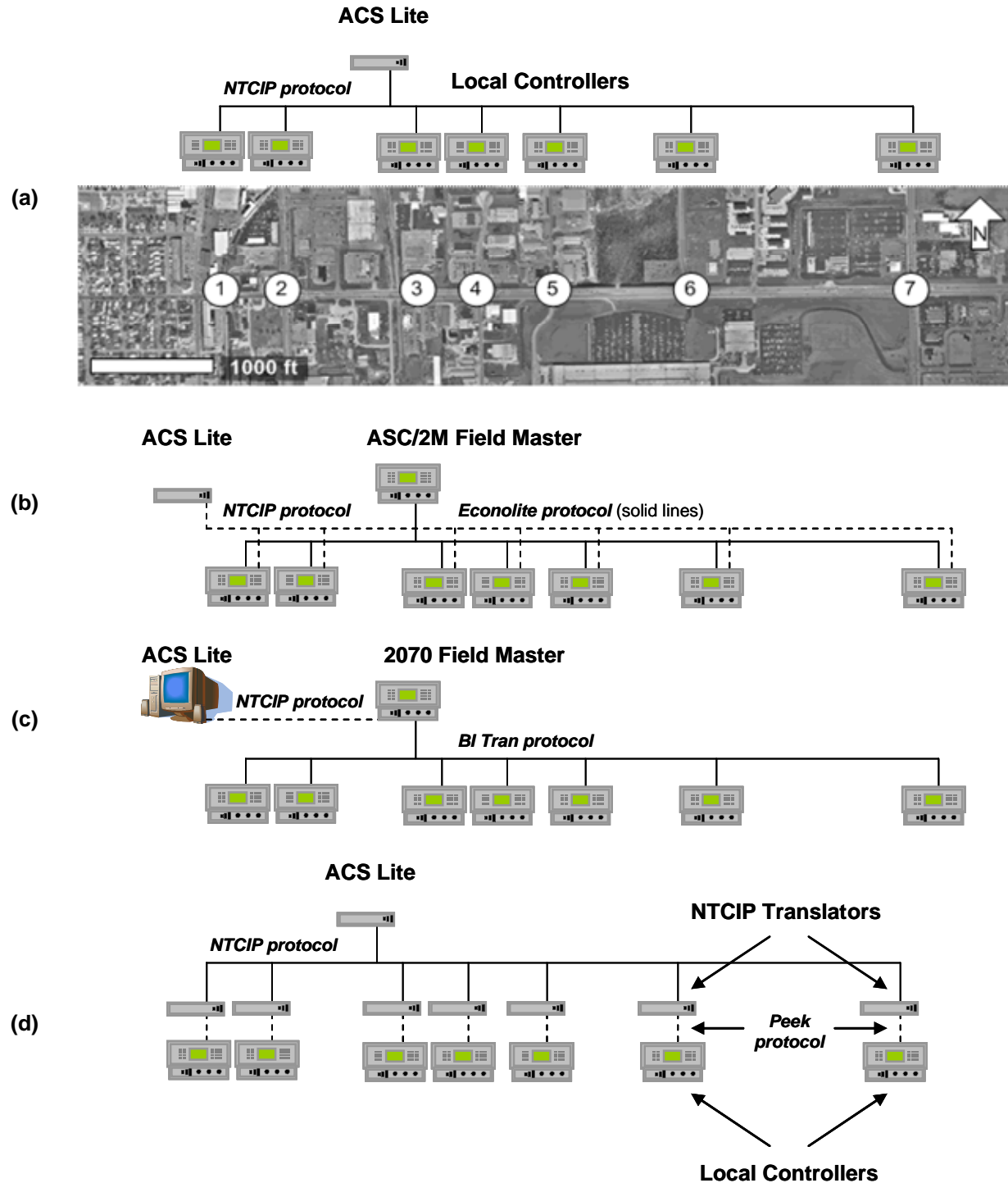


Figure 2. System architectures used with (a) Eagle, (b) Econolite, (c) McCain, and (d) Peek.

Signal Network Layout

FHWA targeted an arterial network as a relatively simplistic initial scope for ACS Lite deployment. Figure 2a illustrates a representative seven-intersection, linear arterial, which served as the basis of most preliminary testing (discussed in more detail later on). ACS Lite is

somewhat flexible in allowing configuration to facilitate progression between any specified pairs of adjacent signals in a network; however, it is not explicitly designed for arbitrarily arranged grid networks. All field tests occurred on linear arterials with the exception of Bradenton, Florida, where the network was L-shaped, with two adjoined, perpendicular arterials.

Controller Hardware/Firmware

The role of the local intersection controller distinguishes ACS Lite from the non-Lite adaptive systems developed by FHWA in the 1980's and 1990's (13). Those distributed-architecture systems have utilized sophisticated algorithms running for each signal in the system. This computation burden generally requires the use of advanced traffic signal controllers, such as a 2070 model controller, and in some cases a dedicated additional CPU for each intersection. In contrast, ACS Lite isolates all adaptive computations to a single processor for a given arterial. This design allows retention of lower-cost controller models, such as the NEMA or 170 models, at each intersection. In field testing ACS Lite, no controller upgrades were required for many of the intersections. That said, all ACS Lite deployments to date have required a relatively low cost firmware upgrade to all local intersection controllers, to enhance communications for ACS Lite. Another "intangible" and often overlooked cost saving benefit comes from the capability to retain familiar controller firmware—the core of which is largely unchanged by the communications upgrade. The time and effort that would otherwise be necessary for staff to learn to use and maintain completely new controller firmware could be significant.

Communications

ACS Lite is designed to operate on typical arterial of 8 to 10 signals, with data communication rates as low as 9600 bits per second (bps). Note that UDP/IP-based communication is also supported. In field testing, existing twisted-pair wiring was used on all four networks, with data rates of 9600 bps to 19,200 bps. In contrast, distributed-architecture adaptive systems may utilize high-speed, peer-to-peer fiber optic communications, which are a costly requirement for both installation and upkeep.

ACS Lite uses NTCIP communications, polling on a per-minute basis for compressed status reports. If a poll request fails, the status report is still available from the local controller until the end of the minute, so the system has ample opportunity to poll again. This affords a measure of insulation from occasional communication errors, which can compromise systems that require per-second communications. This seems to be particularly relevant in the context of wireless communications.

Detector Layout

ACS Lite is designed to be relatively flexible with respect to the size, location, and capability of detectors. This design aims to address concerns that have been raised about the sensitivity of adaptive control performance and cost with respect to detection layouts, and detector accuracy (2). Figure 3 illustrates various detector layout alternatives for ACS Lite. This detection scheme is compatible with typical layouts used for intersections under fully-actuated control. The benefits of this design include the likelihood of a reduced total cost to instrument a typical arterial for adaptive control.

ACS Lite requires stop line detectors for each phase, preferably separated out for individual lane-by-lane monitoring, though lanes serving the same phase/movement may be tied together if necessary. Stop line detectors monitor volume and occupancy on green, and the processing logic accounts or adjusts for the detector length. Detectors sized from 4 to 70 feet long have shown good results. On approaches where progression is desired (generally the arterial approaches), advance loops are used to monitor cyclic flow, to identify the arrival of platoons, and use this data for adjustment of offsets to improve progression. Detector processing has been designed to reduce sensitivity to the accuracy of count data. Count accuracy may deteriorate substantially if a loop begins counting axels instead of cars, or if video detection cannot precisely separate out two vehicles traveling closely together, due to the angle of the camera. As an example of “sensitivity reduction”, consider that green-occupancy flow measures are less sensitive to errors than pure volume-based flow measures. However, the technique is somewhat more involved than measuring only green-occupancy. The complete flow measurement concept is straightforward, but the details are beyond the scope of this paper

The need for accurate turning probabilities and saturation flow rates are also a source of sensitivity (to error) for signal timing optimization. These values are certainly subject to change throughout the day, according to daily travel patterns, and are also influenced by unexpected weather. ACS Lite does not require calibration or configuration of these parameters, and is designed to gauge traffic demand well over a wide range of conditions.

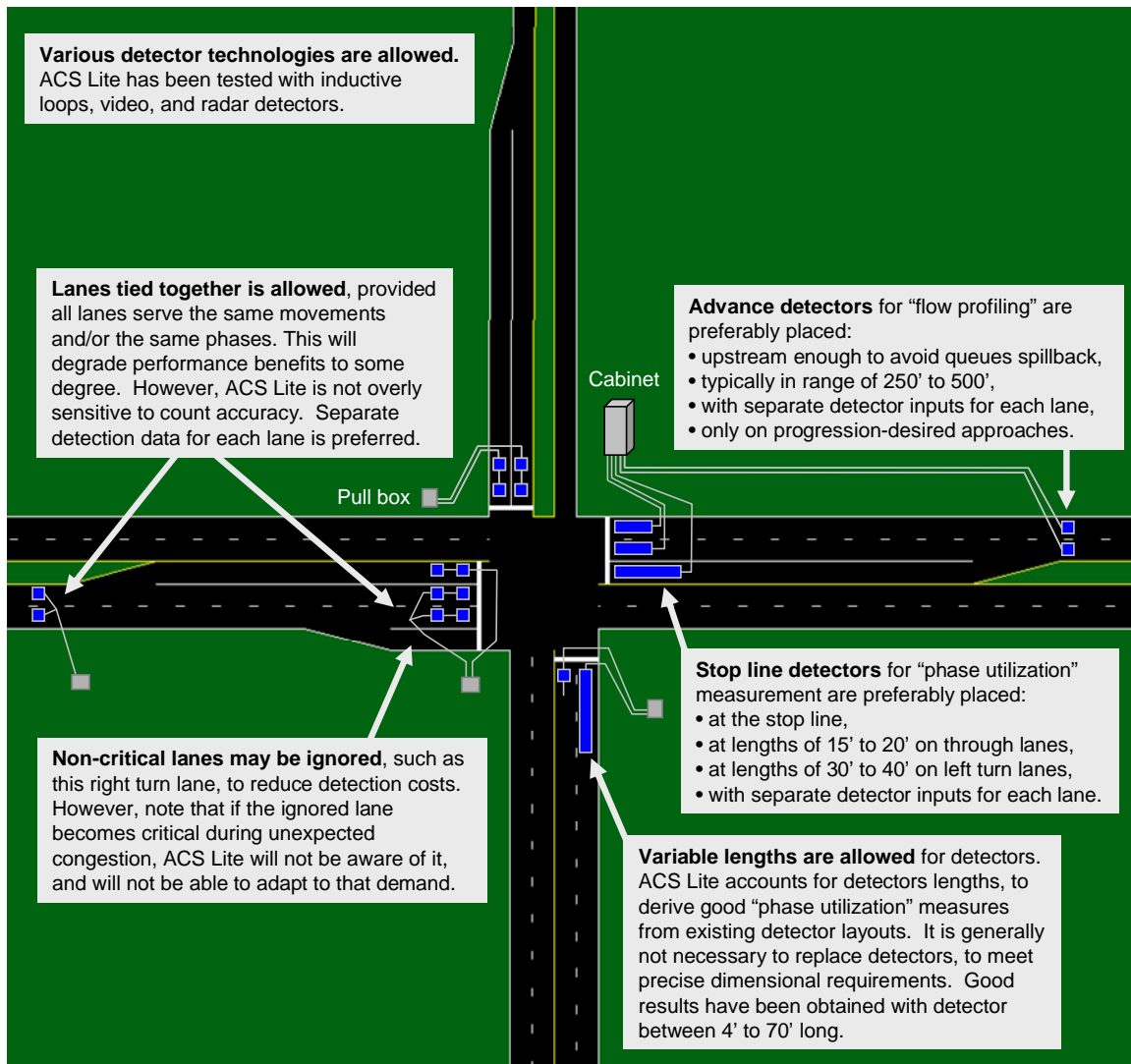


Figure 3. ACS Lite detector layout alternatives.

ADAPTIVE LOGIC

ACS Lite operates by monitoring traffic signals that are running normal coordinated timing plans, and then making incremental adjustments to splits and offsets as often as every 5 to 10 minutes. Cycle length is currently not adjusted by ACS Lite, though future enhancements are planned. The cycle length is dictated by the "underlying" or "baseline" timing plan, which is selected according to the time-of-day schedule (13, 14).

Split Adjustment Logic

Split adjustments are based on measures of the “utilization” of each phase (14). Detector volume and occupancy data is processed, primarily during green intervals, to gauge the amount of time that traffic is flowing across the stop line. ACS Lite estimates the *degree of saturation* of each phase, which is often referred to alternatively as a volume-to-capacity ratio (or v/c ratio). The adjustment logic reallocates split time to balance the degree of saturation across all phases, subject to configured minimum green times, pedestrian interval requirements, and maximum green times (when they are not inhibited during coordination). Thus, time would be reallocated from a phase with an excessively long (i.e., un-utilized) split time, to provide more split time for an oversaturated phase. Figure 4 provides a screen-capture of the ACS Lite’s web-based user interface, which provides a color-coded bar chart indicating the degree of saturation for each phase. These measures are overlaid, in the enlarged view in Figure 4b, on a ring-diagram, to portray the trade-offs of adjusting split time between phases. This particular screenshot illustrates that phase 3 (a cross-street left-turn phase, using typical NEMA phase numbering) is 100% saturated, whereas all of the main-street phases (1, 2, 5, & 6) are less than 60% saturated. The figure also illustrates that phase 3 currently has a 13-second split, which could be reduce to a minimum of 10 seconds, or a maximum of 20 seconds (which corresponding to 3 seconds room to reduce split time, or 7 seconds room to increase time). The adjustment logic also provides an optional “progression biasing” mechanism which distributes “extra” or “slack” green time in the cycle (if it is available) in greater proportion to designated progression phases, which are typically arterial through phases. This feature is effective in exploiting the availability of “slack” time to provide a wider green band for improved progression.

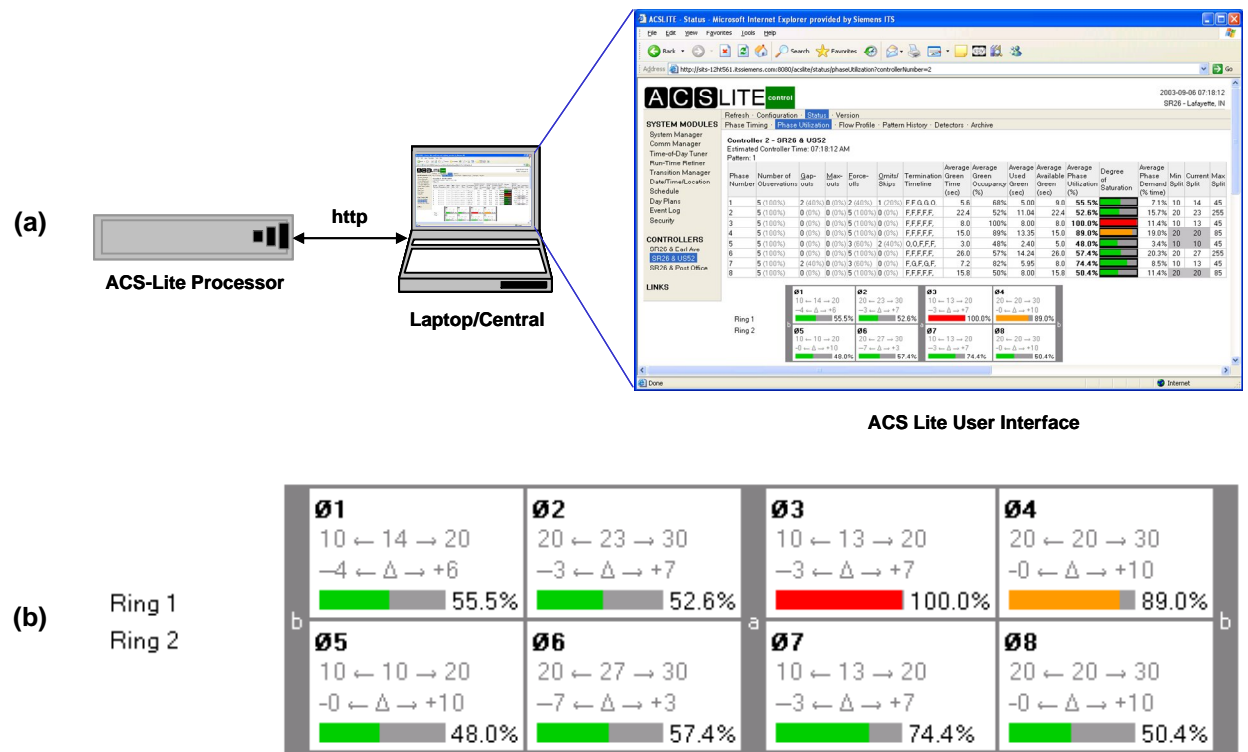


Figure 4. View of (a) the web-based user-interface, with (b) a close-up view of the ring-diagram, showing the degree of saturation of each phase.

Offset Adjustment Logic

Offset adjustments are based on cycle flow profiles, which are compiled by monitoring advance loops on progression approaches. The offset adjustment logic considers only incremental adjustments to the offset: a few seconds earlier, no change, or a few seconds later. This prevents signal transition from having any significant detrimental effect on existing progression. Decisions are made for each signal independently, considering all inbound and outbound designated progression lanes to the intersection (15). ACS Lite computes total (and percentage-wise) arrivals on green for each offset option, and selects the offset that maximizes traffic flow arriving to green lights.

EVALUATION AND RESULTS

ACS Lite has been independently evaluated in a simulation environment, and in field studies in four cities. This section summarizes these evaluations and their corresponding results.

Simulation Environment

Throughout the development of ACS Lite, the CORSIM simulation model has been utilized for testing. A simulation model provides an invaluable basis for research and development, by allowing the construction and exact repetition of specific test conditions as desired. Algorithm development testing included a range of traffic volumes, turning probabilities, queue discharge rates, intersection geometries, detector locations, and detector sizes.

The actuated controller logic in versions 5.1 and 5.2 of CORSIM was enhanced to support multiple coordinated “timing plans” and to emulate contemporary transition logic between timing plans (16). In addition, a *run-time extension* (RTE) was developed to provide an NTCIP interface to simulated controllers in CORSIM. Thus, ACS Lite communicated with the simulation using the same communication protocol it would use to talk to real controllers.

Simulation Evaluation

Purdue University subjected ACS Lite to an extensive battery of simulation tests, making several comparisons with optimized signal timing (14, 17). An arterial model was constructed based on a seven-signal section of State Route 26 in Lafayette, Indiana (pictured in figure 2a). Separate models were calibrated for various flow conditions, including AM-, PM-, and off-peak conditions. The traffic volumes, turning proportions, and saturation flow rates of each model were fed into Synchro 5.0 to optimize signal timing (8). A complete description of all tests can be found in technical reports (14, 17). A few of the results are summarized as follows:

- Starting from optimal signal timing, ACS Lite did not stray from these settings, and showed no significant performance degradation.
- Starting with various “bad” (i.e., suboptimal) offsets values, the ACS Lite offset adjustments (with split adjustments disabled) improved control delay and arterial travel time measures by 0% to 4%.

- Starting with various “bad” splits values, an initial version of the ACS Lite split algorithm (with offset adjustments disabled and no split biasing) made adjustments resulting in between 3.3% less delay to 2.2% more delay, while arterial travel times ranged from 4.9% shorter to 6.8% longer.
- In the context of changing volumes and turning proportions (from the initial values used during off-line optimization), ACS Lite adapted splits and offsets to the changing conditions and provided delay reductions of 7.4% to 28%, while arterial travel times ranged from 6.4% shorter to 3.5% longer.

Each scenario was simulated for five replications. Simulation durations of 75 minutes used to evaluate adjustment algorithms of a single parameter (offsets-only, or splits-only). Simulation durations of 3 hours were used to evaluate simultaneous split and offset adjustments. In the cases where traffic conditions changed (from volumes and/or turning flows of the initial optimized scenario), the changes were assessed in three different patterns as follows:

- A single “step” (i.e., instantaneous) change of traffic conditions after 90 minutes.
- A gradual, linearly increasing change in conditions, starting at 60 minutes and ending at 120 minutes.
- A two step change in traffic conditions, stepping “halfway” at 60 minutes and then stepping “the rest of the way” to new conditions at 120 minutes.

Some of the simulation performance results warranted further investigation to properly digest. For example, degradations in arterial travel time were observed in simulation test cases where the split times of all non-coordinated phases had been lowered to their minimum green times (i.e., to “bad” split values). Time stripped from the non-coordinated phases had been reallocated to the coordinated phases. While these initial settings were suboptimal in terms of overall intersection delay, the greatly increased green time for the coordinated phases—which were serving arterial through movements—provided for much better arterial progression. ACS Lite responded to these initial settings by adjusting the side-street split times higher, with the benefit of reducing the number of side-street phase failures—as much as 70% at one intersection. However, as time was reallocated from the coordinated splits to the side-street splits, the arterial green time was reduced and the measured arterial travel times increased by 6.8%. In this context, performance was qualitatively improved, despite the consequential tradeoff of increased arterial travel time.

Additionally, it is recognized that minor degradations in performance were measured in comparison with signal timings that were optimized with perfect knowledge of the demand volume profile, turning proportions, and saturation flow rates used in simulation. Consequently, these findings were regarded as promising, by having demonstrated a “do no harm” capability relative to good signal settings, and by showing significant benefits in the context of somewhat suboptimal signal timing.

These initial, independently conducted simulation tests served as valuable feedback for the development of ACS Lite, illustrating the need for some improvements, such as:

- Provision of split biasing options for better arterial progression.
- Enhancement of detector processing logic to compensate for short detectors.

These enhancements were later added (prior to field deployment), providing dramatically improved performance in many cases, and striking a better balance between the often competing objectives of reduced arterial travel time and reduced overall intersection delay.

Field Evaluation

ACS Lite was integrated with equipment from each of the four signal controller manufacturers—Eagle, Econolite, McCain, and Peek—and then field tested at four locations across the U.S., as indicated in Table 1.

Table 1. ACS Lite field test locations and evaluation results.

Location	Vendor	Controller Model	Intersection Count	Travel Time	Delay Time	Vehicle Stops	Fuel Usage	1-Year Benefits
Gahanna, OH	Econolite	ASC/2S	9	-1%	0%	-17%	-4%	\$88,000
Houston, TX	Eagle	M50	8	-11%	-35%	-29%	-7%	\$578,000
Bradenton, FL	Peek	3000E	8	-11%	-27%	-28%	-4%	\$757,000
El Cajon, CA	McCain	170E	10					

Sabra, Wang, & Associates independently evaluated ACS Lite performance at each field site, comparing traffic data from signal control without ACS Lite (the *before* period) and signal control with ACS Lite (the *after* period) (18, 19, 20, 21). Data were collected during two-hour AM- and PM-peak intervals, over four consecutive days, which comprised each *before* period and each *after* period. Directional arterial traffic volumes were collected at several locations with pneumatic tubes and counting machines. Arterial travel time, vehicle stops, delay time, and fuel usage were based on data collected from floating cars—two probe vehicles—with on-board GPS receivers. A minimum of 25 runs were conducted traveling the arterial in each direction, during each two-hour peak-period, each day.

The GPS data is processed to determine total travel time, travel time delay, stopped delay time, and number of stops, by link. Stopped delay time is the time a vehicle is stopped while waiting to pass an intersection, which is extracted from the GPS time series as blocks of 5 or more consecutive seconds traveling below 8 kilometers per hour (or 5 miles per hour). Travel time delay is defined as the difference between the actual travel time to travel a link of the arterial and the hypothetical link travel time at the driver’s desired speed. The performance of ACS Lite at each field site is summarized in table 1, for travel time, delay, vehicles stops, and fuel consumption, expressed as a percentage change from performance of the existing field settings. A negative value indicates a decrease in that performance measure, which is an improvement in each of these measures.

Additionally, an analysis was performed to estimate the operational benefits of ACS Lite, by combing the costs of total (travel time) delay, number of stops, and fuel consumption, at the following costs:

- \$12.10 per hour of travel time delay.
- \$0.014 per vehicle stop.
- \$0.59 per liter fuel consumed (\$2.25 per gallon).

Operational benefits were estimated as follows:

- Peak-period benefits were estimated for AM and PM peaks by scaling average peak-period values benefits per vehicle, calculated from floating car data, to average peak-period traffic volumes counted in each arterial direction.
- Daily benefits were estimated assuming that the peaks period (4 hours a day) account for 29% of average daily traffic volume.
- Annual benefits were estimated assuming 260 weekdays per year.

A fuel price of \$0.79 per liter (\$3.00 per gallon) was assumed for the Florida and California field tests. The benefits analysis did not include weekend benefits or side-street traffic benefits.

The evaluation measures from the El Cajon field test are not included in Table 1, due to erroneous controller behavior observed repeatedly at all intersections. The BI Tran 233 firmware, which was specifically modified for ACS Lite communications support, exhibited randomly occurring problems in its coordination logic. For example, controllers failed to correctly synchronize to the programmed offset values in about half of all pattern changes (whether adaptive control was active or not). ACS Lite recognized out-of-sync control errors and reverted to a standby mode for affected intersections. Thus, the corresponding performance measures are not a faithful reflection of ACS Lite's capabilities. It should be noted that ACS Lite did make adjustments to those signals that synchronized to the correct offset value. With correction of the controller issues observed in the field test, it is expected that ACS Lite would achieve the same success with McCain controllers as observed in field evaluations with other controllers.

It should also be noted that during the Gahanna field evaluation, the "normal" ACS Lite offset adjustment algorithm (as tested in simulation by Purdue University) was not applied. Rather, signal offsets were selected on-line using traditional traffic responsive logic, whereby all offsets would be changed to user configured settings to facilitate one-way progression in the direction of prevailing flow, if that prevalence exists. This strategy was specifically requested by FHWA, and does not reflect any shortcoming in the controllers used in Gahanna. While this strategy reduced detection requirements significantly for Gahanna, it would seem that the performance benefits may have been reduced as well. Such a strategy is also influenced strongly by the manual configuration of traffic responsive offsets, and decision thresholds. The "normal" ACS Lite offset algorithms were used at all other field test locations.

In light of the two considerations just discussed, the field evaluation results were regarded as very promising overall, showing significant improvements in measures of effectiveness, ranging as high as a 35% reduction in delay, a 29% reduction in vehicle stops, and a 7% reduction in fuel consumption. Benefit-to-cost ratios were computed for all four sites, showing that the economic benefits of the system (based only on weekday benefits to arterial-only traffic) would be expected to surpass deployment costs within the first year—if not within the first few months.

These benefits found in the field were greater than that found in simulation, which may be the result of multiple factors:

- The field results are based on comparison to existing field timings, which were last optimized three years prior in Gahanna and Houston, and five years prior in Bradenton.
- It is virtually impossible, in optimizing field timing, to acquire consistently stable traffic volumes, turning flows and queue discharge rates with perfect knowledge, as was possible in simulation.
- There were (aforementioned) enhancements to the detector processing logic and split-biasing logic in ACS Lite that occurred after the initial simulation testing.

The performance benefits from the field studies are significant, but not unprecedented. Performance benefits in the same range have also been found with some of the most prevalent adaptive (non-Lite) systems (2). It is also possible that manually updating conventional signal timing plans would yield similar benefits, at least on “normal” traffic flow days. However, as previously mentioned in the *Report Card*, outdated timing plans are more common than up-to-date timing plans (7).

CONCLUSIONS

ACS Lite is an adaptive traffic signal control system designed to achieve FHWA’s goal of a truly, widely deployable solution. Its design strives for practicality, addressing a number of criticisms with adaptive control offerings to date. It achieves a relatively low cost, amongst adaptive systems, by leveraging existing infrastructure investments, including typical detector layouts, typical twisted-pair communications media, and compatibility with lower cost controller models from four major manufacturers. Reduced installation and operational costs are achieved by providing an easy to understand, easy to configure, and calibration-free system, where deployment does not necessarily require staff retraining for new controller firmware. Simulation evaluation and field studies suggest that ACS Lite provides very effective performance, with demonstrated reductions in delay, arterial travel time, vehicle stops, and fuel consumption.

FUTURE DIRECTIONS

A secondary phase of ACS Lite research and development is anticipated in the 2008 to 2009 timeframe, which may address:

- Cycle-time increases/decreases.
- Improved detector diagnostics and fail-safe operations.
- User-interface enhancements.

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