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16. Abstract

The objective of this research project was to enhance and test the platoon identification and accommodation (PIA) system developed by Texas Transportation Institute (TTI) researchers in an earlier research project. The PIA system consists of off-the-shelf hardware and custom software for providing intelligent control at isolated traffic signals. To achieve project objectives, TTI researchers added a software classifier to replace the hardware classifier needed by the original system, added a new module for communication with TS-2 cabinets via serial ports on enhanced bus interface units, extended the system to provide platoon identification and accommodation on both arterial directions, and added real-time performance measurement and adaptive features. Implementation of these enhancements required TTI researchers to re-engineer the original system software. The enhanced system was tested in the lab using cabinet-in-the-loop simulations and then field-tested at two locations in Texas. This report documents the work conducted by TTI researchers in this project.

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ENHANCEMENTS TO PIA SYSTEM FOR REAL-TIME CONTROL AT ISOLATED TRAFFIC SIGNALS

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1. INTRODUCTION

BACKGROUND

A significant number of TxDOT's signalized intersections operate under isolated control and face widely varying traffic conditions throughout the course of a normal day. At many of these signals, it is not uncommon for an approaching platoon of vehicles to face a red signal when it arrives at the stopbar. Often, these platoons are forced to stop because of a single vehicle on a conflicting minor phase, which may be serving the opposing left-turn movement or one of the side-street approaches. This condition results in driver aggravation, excessive stops, higher delay and fuel consumption, and excessive pavement wear and tear.

In TxDOT Project 0-4304, Texas Transportation Institute (TTI) researchers developed and field-tested a platoon identification and accommodation (PIA) system to demonstrate that it is possible to remedy this situation [*1, 2*]. The objective of this research project was to enhance the PIA system and test it at two additional sites. This report documents the work conducted by TTI researchers to achieve these objectives. This chapter describes the original PIA system, identifies its weaknesses and limitations, and outlines the objectives of this research project.

ORIGINAL PIA SYSTEM

Researchers designed the first version of the PIA (PIA-1) system to accommodate platoons approaching an intersection from only one specified priority direction. This section describes the key features of the PIA-1 system.

PIA-1 System Architecture

The PIA-1 system consists of off-the-shelf hardware and custom software developed by TTI researchers to provide platoon detection and platoon progression functions in real time. PIA-1 software, which resides on an industrial personal computer (PC), serves as the brain of the entire system. This software consists of routines to provide communications interface with the hardware. As illustrated in Figure 1, it communicates with the following two external systems via a digital input-output (I/O) card installed in the PC:

1. advance detection, and
2. controller cabinet.

The advance detection system consists of a speed trap (inductive loops or video-based) in each lane located 700-1000 ft upstream of the stopbar, detection unit (loop amplifiers or video processor), and a hardware classifier. The PIA-1 software has a one-way communication link with this system. From the detection system, the PIA-1 software receives detection time, speed, and lane information for each individual vehicle as it passes over the detection zone. As described in the next subsection, the PIA-1 software uses these detector events to identify the presence of platoons.

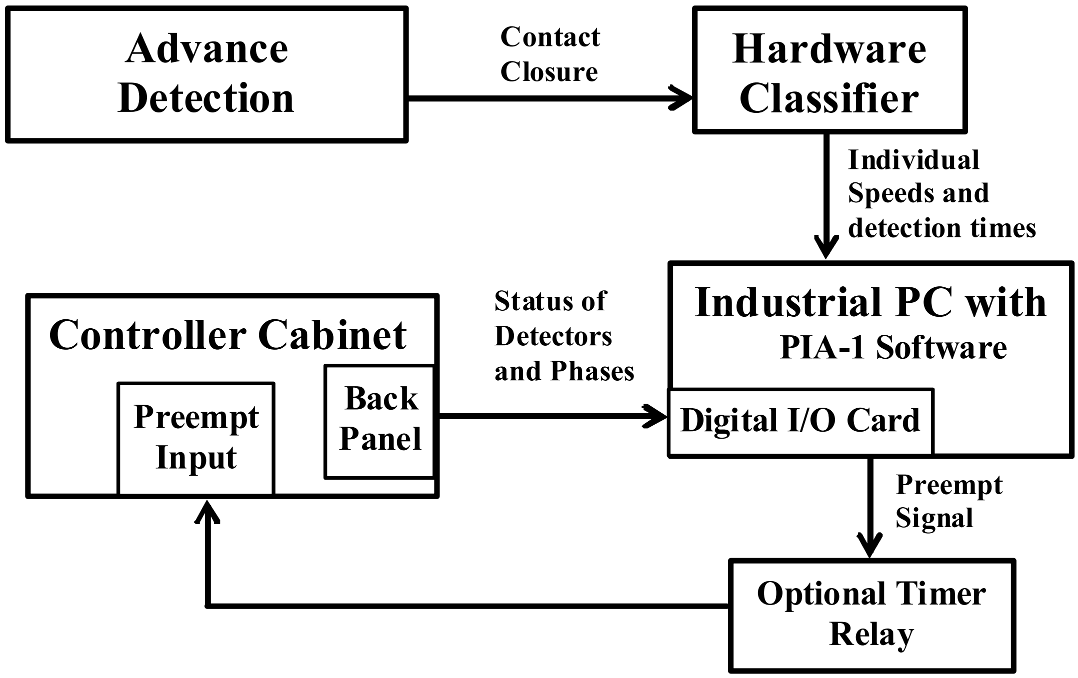

Figure 1. Architecture of PIA-1 System.

The software establishes two-way communication with the controller cabinet. From the back panel, it receives real-time information about the status of all stopbar detectors and signal phases. It obtains the status of signal phases by monitoring the status of A, B, and C bits for each ring in the controller. When appropriate, the PIA-1 software overrides controller operation by sending a signal to the controller through the preempt input panel in the cabinet. The software provides a user-configurable timer to control the maximum duration of any preempt signal in the presence of a call on a conflicting privileged phase. A latter subsection describes the concept of a privileged phase. Developers of PIA-1 recommended an optional timer relay to provide improved fail safety for each override signal.

The reader should note that the PC resides in either the main controller cabinet or an adjacent auxiliary cabinet if the main cabinet does not have sufficient room. Since TS-2 cabinets do not have back panels, system installation in such cabinets requires the installation of a conversion panel and up to two additional bus interface units (BIUs).

Platoon Identification and Accommodation

In addition to routines for providing interfaces with various hardware components, the PIA-1 software contains Platoon Detection (PD) and Platoon Scheduling and Progression

(PSP) modules for providing its core functionality. The PD module implements the platoon detection algorithm described in the following subsection.

Platoon Detection Routine

For each vehicle detected at the advance detector, the PD routine receives speed, detection time, and lane identification (ID) information. Together with user-specified distance of advance detector from the stopbar, it first calculates each vehicle's arrival time at the stopbar. In this calculation, it assumes that each vehicle will stay in the lane in which it was detected and maintain a minimum headway of 2 seconds between the current and the immediately preceding vehicle in the same lane. Thus, if the projected arrival time of a vehicle is the same or less than the immediately preceding vehicle, the routine adjusts the projected arrival time of the current vehicle to the projected arrival time of the preceding vehicle plus the minimum headway value. The routine uses projected arrival times of vehicles for platoon identification and progression. Platoon detection consists of two stages described below.

Initial Platoon Identification Stage

This stage is active when there is no detected platoon. During this stage, the routine identifies if a smallest acceptable platoon exists. This portion of the program uses the following user-specified parameters:

- number of vehicles in the smallest acceptable platoon (n) specified by the user,
- cumulative headway threshold (T_c) specified by the user, and
- preemption advance (P_a) specified by the user.

In real time, the program carries out the following calculation steps:

1. Upon detection of a new vehicle, find the difference (t) between the projected arrival times of the first vehicle and the last vehicle in the group of last n consecutive vehicles.
2. If t is less than or equal to T_c, the smallest platoon meeting the user-specified density criterion has been detected. Go to Step 4.
3. If t is greater than T_c, remove the oldest vehicle from the group of n vehicles. If the signal is red at the projected arrival time of this vehicle, increase by 1 the counter keeping track of the number of vehicles predicted to stop before platoon arrival, and go to Step 1.
4. Create a preemption schedule, which consists of a start and an end time. These times are the predicted arrival times of the first and the last vehicles, respectively, in the group of n vehicles meeting the acceptable platoon criterion. Then, make the following two adjustments to the start time of schedule, and activate the platoon extension stage described in the next subsection:
    a. Advance the time to account for the number of vehicles predicted to stop. This adjustment provides queue clearance time before a predicted platoon arrives.

   b. Advance the start time by an additional amount equal to P_a. This factor allows the user to make adjustments due to site-specific factors.

It should be noted that the number of approach lanes, speed limit, and driver behavior play an important role in the selection of values for algorithm parameters *n* and *Tc*.

Platoon Extension Stage

This stage activates as soon as a platoon has been detected and remains active as long as the platoon schedule has not expired. During this stage, the PD routine evaluates each additional vehicle to determine if it is part of the previously detected platoon or if it will be in its dilemma zone at the scheduled preemption end time. If either of these conditions is true, the algorithm extends the preemption termination by an appropriate amount of time. This mode of algorithm uses the following three user-specified parameters:

- average headway threshold (T_h),
- extension to last vehicle in the platoon (T_e), and
- preemption clearance (P_c).

The PD routine uses the first two thresholds to assess if a new vehicle is part of the current platoon. In this mode, the program performs the following calculation steps:

1. Wait for a new detection. If the platoon progression schedule expires during this wait, switch to the initial platoon detection stage described above. Note that a platoon progression schedule expires if the current time is larger than the scheduled end time. If a new vehicle arrives before expiry of the progression schedule, go to the next step.
2. Perform the following two calculations:
   a. Calculate the average headway for all vehicles in the platoon, including the new vehicle. If this value is less than or equal to T_h, the new vehicle is part of the platoon.
   b. Calculate the headway between the new vehicle and the last vehicle in the current platoon. If this value is less than or equal to T_e, the new vehicle is part of the platoon.
3. If the new vehicle is part of the current platoon, change the platoon progression end time in the schedule to the projected arrival time of the new vehicle and go to Step 1.
4. If the new vehicle does not meet extension criteria 2a and 2b, compare the vehicle's projected arrival time with the end time in the scheduler with P_c to determine if any additional clearance time is needed. Change the scheduled end time by the calculated adjustment and switch to the initial platoon identification stage. Note that setting P_c equal to 2.5 seconds is equivalent to providing dilemma zone protection to this last vehicle.

Platoon Scheduling and Progression Module

The PIA-1 system had a simple PSP module, which activated a preemption signal if the current clock time fell within an active schedule with valid begin and end times. One reason for this simplicity was the fact that the system provided platoon progression in only one arterial/priority direction. The second reason was that the use of a preempt signal to override normal controller operation did not require keeping track of the signal phases.

The PIA-1 system provided excellent level of service to the priority phase by penalizing conflicting traffic. Initial field testing of this system revealed that traffic conflicting with the priority phase experienced unacceptable delays. Thus, researchers added constraints to the system to lessen these delays. The next subsection describes these constraints.

Constraints on Platoon Accommodation

To minimize negative impacts on traffic conflicting with the priority direction, the PIA-1 system allowed enforcement of certain constraints on platoon progression via user-configurable parameters. These configurable parameters included:

- A maximum (Max) timer to restrict the length of controller override signal in the presence of demand at any conflicting phase. This feature is similar to the Max timer in modern traffic controllers.
- A preempt-revert timer that restricted the controller override for a specified time before allowing the next controller override. This timer locked the algorithm from issuing another preempt for a specified duration after termination of one preempt. This feature is similar to the "Red Revert" feature in traffic controllers.

Modern controllers provide a phase skip flag on preemption programming screens. When a user selects this flag as true, the controller ignores (or skips) all phases with active detection and immediately activates the preempt. This all or nothing selection is not useful under conditions where the system can benefit by skipping only a subset of conflicting phases. To accommodate such situations, TTI researchers implemented the concept of a privileged phase in PIA-1. A privileged phase was defined as a phase that cannot be skipped:

- if a detector calling the phase is active, the phase is red, and the PIA-1 software activates the controller override to progress a detected platoon, or
- if a detector calling the phase becomes active while the controller override via preempt is active.

Thus, a privileged phase with demand could not be skipped twice to serve platoons on the priority phase.

Needed Improvements and Refinements

The PIA-1 system was designed for real-time control at isolated signals. However, it had the following limitations:

- It provided platoon identification and progression in only one selected direction.
- Its application in TS-2 cabinets required a conversion panel and additional BIUs, increasing installation cost by approximately $1500 per such site.
- It was not capable of dynamically adjusting its operation to accommodate varying traffic conditions at minor approaches to the intersection.

Furthermore, the use of a $3000 hardware classifier for obtaining speeds of individual vehicles was overkill, especially when it provided no control to correct for detection errors.

RESEARCH OBJECTIVES

The objective of this project was to make the following refinements to the PIA-1 system and test it at two additional sites:

- expand the system for application to both arterial approaches,
- replace the hardware classifier with a software classifier,
- provide standardized installation in TS-2 cabinets, and
- identify, evaluate, and implement other enhancements.

An additional objective was to evaluate the feasibility of incorporating functionalities of Detection Control System (DCS) and Advanced Warning of End of Green System (AWEGS) into the PIA system. DCS was developed by TTI researchers to provide dilemma zone protection at high-speed isolated signals [*3*]. Similarly, AWEGS was developed by TTI researchers to provide advance warning of end of green to traffic approaching a high-speed isolated signal [*4*]. The objective of both these systems is to improve safety. On the other hand, the objective of the PIA system is to improve traffic operations, while maintaining safety. All three real-time systems have several common features, which include: real-time monitoring of detectors and phases at the intersection and use of advance detection of individual vehicles.

The remainder of this report documents the work conducted in this project to develop and test the second-generation PIA system, referred to as the PIA-2 system in this report. Chapter 2 describes the details of enhancements made to the PIA system. Chapter 3 describes field installation and evaluation of the PIA-2 system, and Chapter 4 provides conclusions and recommendations for future enhancements.

2. PIA SYSTEM ENHANCEMENTS

OVERVIEW

The objective of this project was to enhance the original PIA system by expanding its functionality and refining its software and hardware components. Achieving this objective required a thorough evaluation of the architecture of the PIA-1 system, including its software components. This evaluation showed that the most complex task was to expand the scheduler for providing platoon accommodation in both arterial directions, and that the best way to produce an enhanced PIA system with all desired enhancements was to reengineer the entire software. In this process, researchers performed the following work:

- Developed a new user interface (including new screens and additional data structures) to accommodate up to two priority directions on the arterial.
- Replaced the hardware classifier with a software classifier routine. Like the hardware classifier, this routine takes contact closure information from a speed trap and produces detection time, speed, and length and lane identification for each detected vehicle.
- Retained the platoon identification algorithm of PIA-1, but restructured the code to duplicate it for application to both directions.
- Expanded the controller cabinet interface routine to provide serial communication with TS-2 cabinets via enhanced BIUs.
- Developed a new scheduler to accommodate platoons in both directions.
- Expanded the controller override mechanism to include phase holds in conjunction with preempts or alone. The latter option produces a less intrusive system. This feature also produces more efficient termination of controller override.
- Significantly expanded the real-time monitoring and performance generation capability of the PIA software to provide adaptive features. A subset of these measures is used by the PIA-2 system to adapt its operation to accommodate changes in demand on privileged phases. The real-time performance measurement mechanism of the PIA-2 software cuts across several software modules, and it is beneficial to describe its key features and algorithms before describing other key components of the PIA-2 software. The following subsections achieve this objective.

Real-Time Monitoring and Performance Measurement

During its operation, the PIA-2 system monitors all signal phases, stopbar detectors, and advance detectors by checking their status every 15 to 20 milliseconds. Then, it calculates appropriate statistics for later or future use. As part of the initial setup and configuration of the PIA-2 system at a site, the user provides the following information, which is used by the program in calculating these statistics:

- all phases and their maximum and minimum green times in the controller,

- all stopbar detectors and phases they are assigned to,
- arterial priority phases and advance detectors assigned to them, and
- lane identification and distance of each advance detector's leading edge from the stopbar. The program automatically calculates the distance (leading edge to leading edge) for a pair of detectors forming a speed trap in each lane.

Stopbar Detectors

For each stopbar detector, the program compares the current detector status and system time with previous detector status and time to obtain the durations for which a detector is occupied and unoccupied. Figure 2 provides the logic for these computations. In addition, the program keeps track of the beginning and end times of detector on and off events for further processing. If desired by the user, the program also logs these data for off-line processing.

Signal Phases

In real time, the program also keeps track of the cycle-by-cycle lengths of green (G), yellow (Y), and red (R) indications for signal phases using a logic similar to that used for monitoring stopbar detectors. Figure 3 describes the logic for these calculations. It should be noted that the PIA-1 software monitored the status of A, B, and C bits for rings in the controller to deduce the status of phases. In PIA-2, researchers have changed this process to monitor the status of green and yellow intervals of each phase. The program deduces red status from this information by invoking the fact that a phase is red if it is neither green nor yellow. The PIA-2 software compares real-time green phase lengths with corresponding minimum and maximum values to determine phase utilization on cycle-by-cycle and daily bases. In addition to the lengths of G, Y, and R intervals for each phase, the program keeps track of the beginning/ending times of these intervals for further processing described below in the "Other Calculated Performance Measures" section.

Advance Detectors

Figure 4 shows the standard configuration of advance detectors, which consists of two inductive loops to form a speed trap identified as advance detector A (ADA) and advance detector B (BDA). The locations of these detectors depend on the approach speed. At program configuration time, the user specifies the lane identification and distance of leading edges of the two detectors from the stopbar. From the distance information, the program automatically calculates the distance between the leading edges of the two detectors.

In real time, the program keeps track of the times ADA and BDA activate and deactivate due to the passage of a vehicle. In addition, the program calculates occupancy (the length of time each detector is active) of each detector using logic similar to that described in Figure 2. Recall that this logic keeps track of the "on" and "off" times of a detector to calculate occupancy. The program performs consistency checks on the calculated occupancy values. It should be noted that the value of occupancy for each detector event (that is, a vehicle passing over ADA or BDA) depends on the detector length, the vehicle length, and the speed of vehicle. Of these, the detector length is fixed. Therefore, the objective of the classifier is to determine speed and length of each vehicle.

```
Begin Loop
        Wake up
        Get CT
        Get CDS
        ΔT = CT – PT
        If (PDS = Off and CDS = Off)
                UnOcc = UnOcc + ΔT
        Else If (PDS = Off and CDS = On)
                UnOcc = UnOcc + ΔT
                Save UnOcc
                Occ = 0
        Else If (PDS = On and CDS = On)
                Occ = Occ + ΔT
                PS = CS
        Else If (PDS = On and CDS = Off)
                Occ = Occ + ΔT
                Save Occ
                UnOcc = 0
        End If
        PDS = CDS
        PT = CT
        Hibernate
End Loop

Where:
        CT    = Current time, milliseconds (ms)
        PT    = Previous time, ms
        CDS   = Current detector status, On or Off
        PDS   = Previous detector status, On or Off
        Occ   = Length of time detector occupied, ms
        UnOcc = Length of time detector unoccupied, ms
```

Figure 2. Logic for Calculating Detector Occupancies.

```
Begin Loop
    Wake up
    Get CT
    Get CPS
    ΔT = CT – PT
    If (CPS = G and PPS = G)
        LG = LG + ΔT
    Else_If (CPS = Y and PPS = G)
        LG = LG + ΔT
        Save LG
        LY = 0
        Hibernate
    Else_If (CPS = Y and PPS = Y)
        LY = LY + ΔT
    Else_If (CPS = R and PPS = Y)
        LY = LY + ΔT
        Save LY
        LR = 0
    Else_If (CPS = R and PPS = R)
        LR = LR + ΔT
    Else_If (CPS = G and PPS = R)
        LR = LG + ΔT
        Save LR
        LG = 0
    End If
    PPS = CPS
    PT = CT
    Hibernate
End Loop

Where:
    CT    = Current time, ms
    PT    = Previous time, ms
    CPS   = Current phase status, G, Y, or R
    PPS   = Previous phase status, G, Y, or R
    LG    = Length of green that just ended, ms
    LY    = Length of yellow that just ended, ms
    LR    = Length of red that just ended, ms
```

Figure 3. Logic for Calculating Lengths of Phase Intervals.

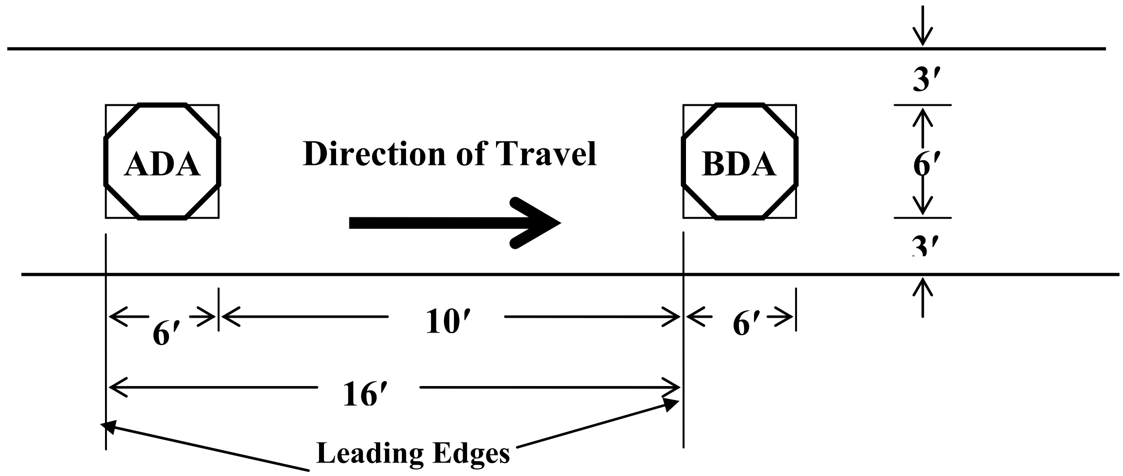

Figure 4. Configuration of Advance Detector in a Lane.

The program uses detection times and occupancies from ADA and BDA to obtain three real-time measures described below.

<u>Vehicle Counts</u>
The program keeps track of counts of vehicles calculated for ADA and BDA separately. At the present time, these counts are not used during real-time PIA operation. Daily counts are optionally logged for offline use. The counts can also be displayed in real time by selecting this view.

<u>Vehicle Speeds</u>
The program uses the following methods to calculate the two speed values it uses to determine projected arrival times of vehicles at the stopbar:

- Speed_1 = $(D \times 1000)/\Delta_{On}$
- Speed_2 = $(D \times 1000)/\Delta_{Off}$

Where:

D = distance between leading or trailing edges of ADA and BDA (16 ft for standard configuration),

Δ_{On} = time difference between when a vehicle hits the leading edge of ADA and when the same vehicle hits the leading edge of BDA (sec), and

Δ_{Off} = time difference between when a vehicle hits the trailing edge of ADA and when the same vehicle hits the trailing edge of BDA (sec).

Note that the multiplier value of 1000 converts time from milliseconds to seconds. The program makes consistency checks on detector "On" and "Off" events before calculating speeds. If data for either one of them fail the test, the speed is flagged to be "bad." If both speed values pass the goodness test, it calculates the average speed. If only one value is good, it uses the good speed. If both values are bad, it ignores the detection.

Vehicle Lengths

As stated earlier, the occupancy of a detector is a function of detection length (length of vehicle plus detector length) and vehicle speed. Using this information, the program calculates vehicle length (L) using the following relationship:

$$L = (\text{Speed} \times \text{Occupancy} \times 1.47) - \text{Detector-Length}$$

In this calculation, the program uses the average value of occupancies for ADA and BDA if both values are good. If not, it uses the good values. If both occupancies are bad, the detection is ignored.

Additional Derived Performance Measures

Demand Estimation

As the program obtains information from each stopbar detector and associated signal phase, it combines individual pieces of information from these two sources into data or statistics useful for incorporating adaptive features into a real-time system such as PIA. These data and statistics include assessment of: cycle-by-cycle demand, phase utilization, and delay estimates.

In this real-time process to derive performance measures, the program uses a rolling horizon approach to calculate the length of cycle immediately preceding the termination of a signal phase interval. Figure 5 illustrates this process.

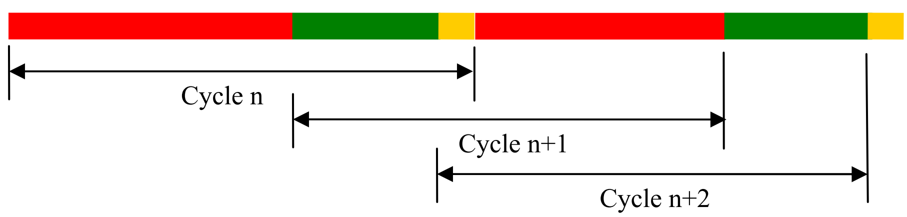

Figure 5. Dynamic Calculation of Cycle Length for a Signal Phase.

In the above illustration, length of Cycle n is equal to the sum of R, G, and Y intervals at the termination of the yellow interval. Similarly, lengths of Cycles n + 1 and n + 2 are calculated at the termination of intervals R and G, respectively. The program uses this procedure to calculate the cycle lengths for each phase. The real-time lengths of contiguous cycles for the same phase and cycle lengths for different phases can be different. During light traffic conditions, these lengths can have significant cycle-to-cycle variations. However, during heavier traffic conditions, signal cycle length will tend to converge toward a background cycle length that is equal to the sum of maximum green, yellow, and all-red times for all phases in the critical ring.

Previous research has shown that volume to saturation flow ratio for a signal phase can be approximated by using the following relationship [5]:

$$V/S \approx g_s/(r + g_s) \qquad (1)$$

Where:

V	=	volume, vehicles per hour (vph)
S	=	saturation flow rate, vehicles per hour (vph)
g_s	=	saturated portion of phase (seconds), and
r	=	measured duration of red interval immediately before g_s (seconds).

For an actuated phase, g_s is the length of green phase minus gap time and lost time at the start of the green phase. Thus, g_s is equal to the effective length of the green phase, the time required to clear a standing queue plus any vehicles arriving while the queue is clearing. One exception is the low-demand scenario where minimum green time is sufficient to service it. In this case, effective length of the green phase cannot be estimated using actual phase length. Furthermore, the following two points should be noted:

- If traffic arriving at the subject phase is not influenced by any upstream signal, cycle-by-cycle variations in effective length of phase will be due to variations in demand.
- If traffic arriving at the subject phase is influenced by an uncoordinated upstream signal, cycle-by-cycle variations in effective phase length may be amplified. Such amplifications will be the result of cyclic platoon arrivals at different times combined with random arrivals.

If the subject phase receives traffic from an upstream signal, the first part of green may or may not indicate the saturated portion of green depending on when the platoon arrives from the upstream signal. Figure 6 illustrates one possible scenario.

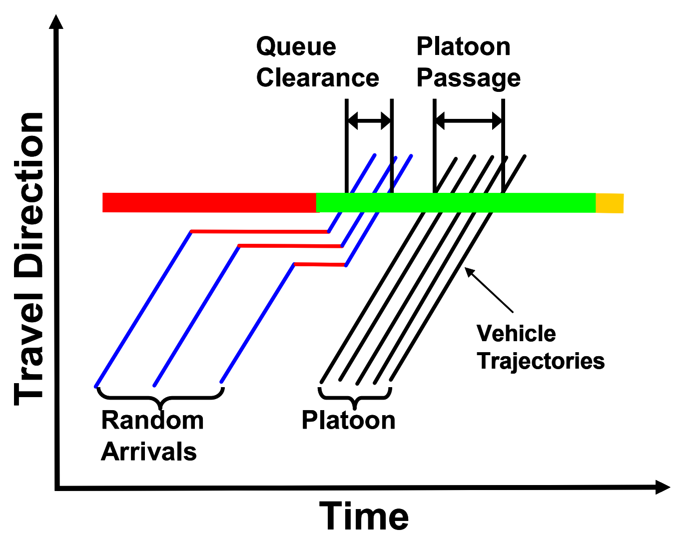

Figure 6. Possible Green Utilization of a Coordinated Phase.

In this scenario, two distinct portions of green phase serve traffic demand. The first portion is the queue clearance time, which begins after some lost time and ends when the standing platoon has cleared. The second portion begins following an unused portion of green after queue clearance. During this period, the green phase serves a compact platoon arriving from the upstream signal. Thus, the saturated portion of green is equal to the sum of queue clearance and platoon passage times. Vehicle trajectories shown in Figure 6 for illustration purpose are not available from standard stopbar detection. In the absence of this information, saturated portions of the green phase can be derived by fusing real-time phase and stopbar detector status data. Figure 7 illustrates the fusion of these two data streams.

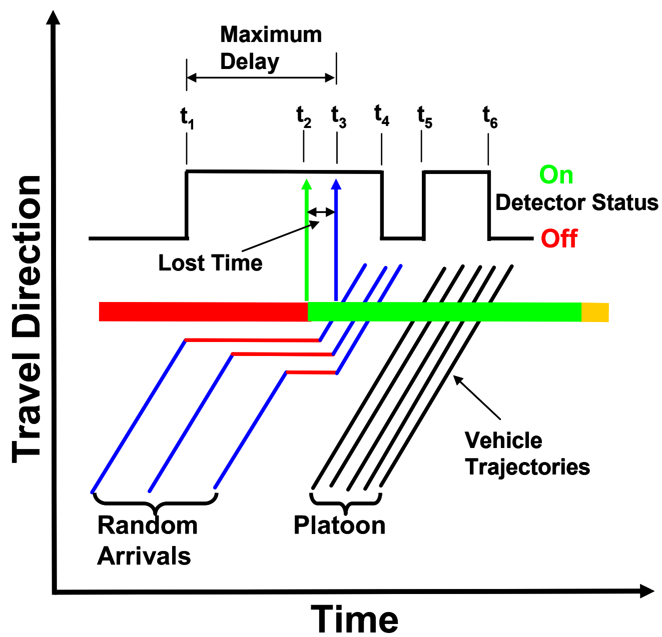

Figure 7. Fusion of Phase and Detector Status Data.

Figure 7 shows that the stopbar detector remains "On" from the time the first vehicle in the queue arrives until the queue clears. If the lost time (L) is known, or can be assumed:

- Maximum Delay = $(t_2 - t_1) + L$, where $L = t_3 - t_2$;
- Queue Clearance Time = $(t_4 - t_2)$;
- Platoon Passage Time = $(t_6 - t_5)$; and
- A value of $(t_5 - t_4)$ greater than zero indicates inefficient use of the green phase. In the case of a coordinated phase, this inefficiency could be caused by an early return to green or a bad offset.

Where:

t_1 = time the first vehicle in the queue arrived,
t_2 = time the green phase started,
t_3 = time the first queued vehicle cleared past the stopbar,
t_4 = time the queue cleared,

t_5 = passage time of first vehicle in the platoon, and
t_6 = passage time of the last vehicle in the platoon.

It should be noted that a value of $(t_2 - t_1)$ greater than or equal to the length of the red interval indicates phase failure, a condition where the green phase maxes out prior to clearing the queue.

In Figure 7, g_s is equal to the sum of queue clearance and platoon passage times, which is equal to detector occupancy on green. In reality, however, the detector profile will not be as clean as shown in this illustration. Depending on the length of the stopbar detector, approach speed, and platoon dispersion, there may be short periods of detector "Off" times between the passages of vehicles. Using a calibrated threshold, such periods should be ignored for the purpose of estimating g_s. Once g_s has been estimated, a rearranged form of Equation 1, shown below, can be used to estimate hourly demand on a cycle-by-cycle basis:

$$V \approx (g_s/(r + g_s)) \times S \qquad (2)$$

This equation assumes lane-by-lane detection and known saturation flow rate (S) for the subject lane. This approach will generally overestimate demand when a single detector (actual or effective due to a common lead-in wire) is used to cover multiple lanes. Such estimation, however, will converge to the critical lane demand during heavier flow conditions.

Phase Utilization

Using the phase maximum (Max) and minimum (Min) green times programmed in the controller and replicated by the user in PIA-2 software during configuration, the program keeps track of the number of times each green phase:

- was terminated after serving Min green. Using the detector occupancy profile, the program also keeps track of the number of times the queue cleared before reaching Min green;
- was larger than Min green and smaller than $0.5 \times (\text{Max} - \text{Min})$;
- was larger than or equal to $0.5 \times (\text{Max} - \text{Min})$ and smaller than Max;
- was terminated by its Max setting; and
- was larger than its Max setting. It should be noted that this statistic can be positive only for priority phases. For a priority phase, this statistic indicates the number of times the PIA-2 system held a green phase beyond its Max time.

Controller Override Statistics

The program also keeps track of platoon progression data by keeping logs of each platoon detection and progression event. The data log includes identification of priority phase, start time of platoon progression, end time of platoon progression, and controller override mechanism (a preempt or a phase hold). The user can perform offline processing of these detailed logs to calculate various statistics. The program also creates a daily log of platoon detection statistics for each priority phase. This log stores the number of platoons meeting the detection criterion, the number of platoons meeting the platoon extension criterion, and the number of platoons meeting the average platoon criterion.

Dynamic Privileged Phases

Chapter 1 described the concept of privileged phases implemented in PIA-1. Although that implementation provided the ability to exercise improved preemption control, its static nature did not permit the best possible traffic control under all traffic conditions. The implementation of real-time performance measurement in PIA-2 provided the means to replace the static privileged phase treatment of PIA-1 by a more robust dynamic control algorithm. The new algorithm in PIA-2 uses real-time phase utilization data to dynamically determine when, and to what extent, a nonpriority phase can be taxed to provide favorable treatment to its conflicting priority phase(s). To accomplish its objectives, the algorithm uses three user-defined parameters – minimum delay (D_{min}), maximum delay (D_{max}), and delay increment (I) – for each nonpriority phase. Given these parameters, the algorithm calculates a real-time delay value (D) for each nonpriority phase using the following logic:

1. set D equal to associated minimum delay value,
2. wait for the phase (g) to end, and then proceed to Step 3, and
3. change D as per the following logic and go to Step 2:
   If [$g < 0.5 \times (Max - Min)$] $D = D + I < D_{max}$
   If [$g \geq 0.5 \times (Max - Min)$] $D = D - I > D_{min}$
   If [phase maxed out twice in a row] $D = D_{min}$
   If [phase terminated by PIA while demand] $D = D - (2 \times I)$.

When waiting for initial platoon detection, the PIA system ignores any vehicle call on a nonpriority phase for a duration equal to the current delay value. Thus, phases with light demand will be taxed more than phases with heavy demand. Note that setting D_{max} equal to zero is equivalent to privileged phase assignment in PIA-1. Also note that any delay (D) on a dynamic privileged phase does not affect normal controller operation.

Feasibility of Incorporating DCS and AWEGS Functionalities

To determine the feasibility of adding DCS and AWEGS functionalities into PIA, researchers evaluated how these two systems operate as compared to the PIA system. The key features of DCS and AWEGS are summarized below.

- DCS provides dilemma zone protection at a high-speed approach by holding the green phase serving that approach until it is safe to terminate the subject phase. It makes phase termination decisions by evaluating data from advance detectors and stopbar detectors and signal phases. To terminate a phase, the system places a force-off and removes the hold. As such, the DCS system overrides normal controller operation only when the subject phase is green.
- The main objective of AWEGS is to predict the termination time of high-speed through phases and provide advance warning by turning on flashing beacons a

few seconds before phase termination. AWEGS works with the standard dilemma zone system and, like DCS, is only active when the main-street through phases are green. AWEGS uses phase holds of short duration to handle some traffic conditions. However, in general it is more passive than the other two systems.

The PIA system is different from DCS and AWEGS in the following ways:

- it is not restricted to exercising control only when the phase is green; in other words, it can take over no matter what the status of a priority phase is; and
- it takes over controller operation only when a platoon is detected and it is not constrained by traffic conditions on privileged phases or due to other user-defined parameters (i.e., Max timer).

The PIA system considers dilemma zone protection only when terminating its controller override signal (preemption or phase hold). It does not contain features to provide dilemma zone protection when: (1) the controller override terminates due to Max timer expiration, (2) the subject phase remains green after the system has removed its override signal, and (3) the signal is under normal control. To provide full-time dilemma zone protection similar to DCS, the PIA system requires the incorporation of DCS decision-making logic and controller override mechanism to exercise full control of subject green phases by employing phase holds and force-offs. These modifications are feasible, but could not be implemented due to resource constraints. Researchers determined that the incorporation of AWEGS functionality into the PIA system is relatively easier and less involved than that of DCS. The bulk of the effort required to achieve this objective involved reengineering and integration of AWEGS prediction algorithm into the PIA system. Researchers designed and developed PIA-2 data structures and codes to facilitate such integration. However, this project did not have sufficient resources to support work needed to complete the integration and testing process.

ARCHITECTURE OF THE PIA-2 SYSTEM

As described in the previous chapter, system software is the brain of the PIA-2 real-time traffic control system. Figure 8 provides an overview of the PIA-2 system architecture from this perspective. As illustrated in this figure, the system software consists of four main modules:

- the Software Classifier (SC) module,
- the Platoon Detection (PD) module,
- the Platoon Scheduling and Progression (PSP) module, and
- the (TS-1 or TS-2) Controller Cabinet Interface (CCI) module.

Like its predecessor, the PIA-2 system software runs on a field-hardened industrial personal computer (PC) that resides in the traffic controller cabinet or an auxiliary cabinet if the traffic controller cabinet does not have room to house additional equipment. The following sections provide a description of each of the PIA software modules.

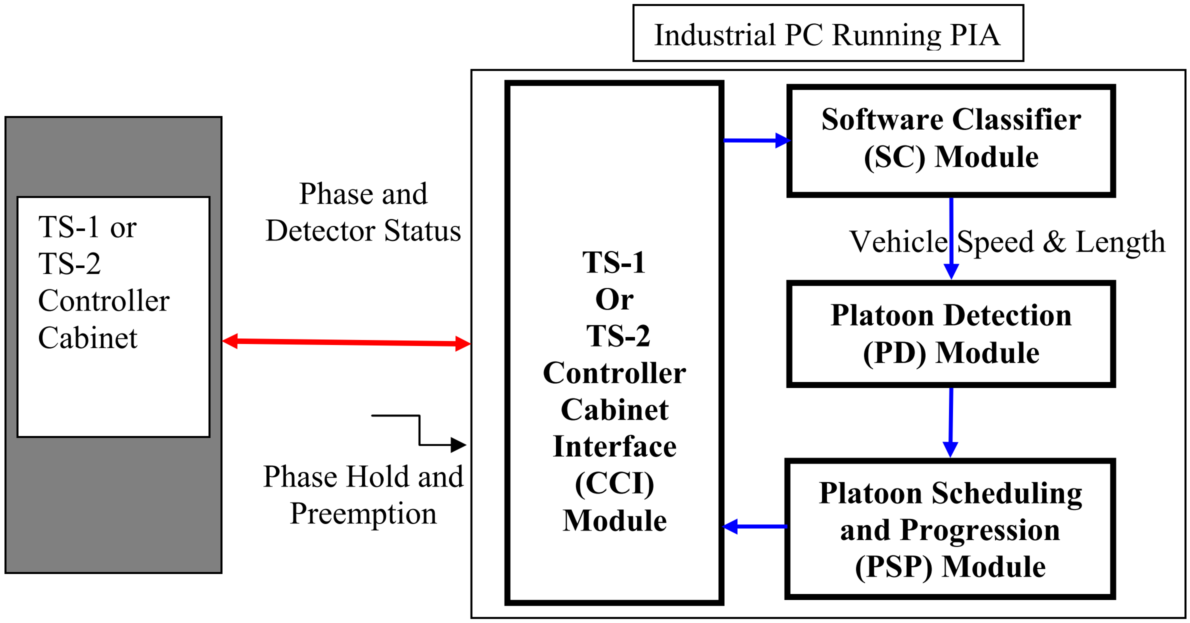

Figure 8. PIA-2 System Architecture.

Software Classifier Module

Researchers added this module in PIA-2 to replace the hardware classifier used by the earlier system. The purpose of the SC module is to provide advance detection of individual vehicles on a per-lane basis for one or both main-street approaches. For each vehicle, it obtains or calculates (as described earlier) speed and length. Then, it passes this information to the PD module along with the lane number in which the vehicle was detected. The SC module requires the following components to be installed at each PIA site:

- one speed trap (inductive loops or video camera-based) per lane or a smart sensor capable of detecting individual vehicles and providing per-vehicle speed, length, and lane number information;
- appropriate detection unit(s) (loop amplifier or video processor) to provide contact closure information from the trap (both loops) or a serial message that contains the per-vehicle information required by the PIA system in case a smart sensor system was used instead of loops; and
- communication links between the trap detectors and detection unit(s) or smart sensor and the PIA system (hardwired or wireless).

The SC module receives individual actuations (contact closure information) from traditional advance detectors (i.e., inductive loop speed traps) through the CCI module and processes the actuations to calculate the speed and length of the detected vehicles upstream of the intersection. If a smart sensor provides advance detection, the SC module deciphers serial messages sent by the smart sensor and extracts information required by the system. The SC module uses the proprietary communications protocol specifications of the smart sensor for this purpose.

Controller Cabinet Interface Module

The CCI module provides the interface between the PIA system and the traffic controller cabinet. The PIA system requires several inputs from the controller cabinet, including green/yellow status of each signal phase at the intersection and on/off status of each stopbar detector at the intersection. The PIA system also sends appropriate signals to the controller cabinet any time it activates preempts or holds to progress detected platoons on the main street. The PIA system also receives data from advance sensors. These data consist of detector actuations if advance detection uses a pair of inductive loops (a trap) in each lane and detection messages if a smart sensor was used for advance detection.

The CCI subsystem consists of a software module and a number of hardware components depending on the type of controller cabinet (TS-1 or TS-2) used at the intersection.

TS-1 Cabinets

In TS-1 controller cabinets, the CCI subsystem requires the National Instruments Data Acquisition PCI-6527 digital input-output (NI-DAQ) card, which is installed in the industrial PC running the PIA software. The NI-DAQ card has 24 inputs and 24 outputs. The digital I/O inputs obtain real-time status (green/yellow) of each active phase and the on/off status of each stopbar detector at the intersection. The input channels also receive contact-closure signals from advance detection in cases where such detection is provided using inductive loop detectors or a video-based vehicle detection system. The PIA system installation at a standard eight-phase intersection requires two NI-DAQ cards. However, depending on the number of phases, the number of stopbar detectors, and the number of advance detection traps, the PIA system may need only one NI-DAQ card. The PIA system uses a maximum of five output channels on the NI-DAQ card (up to two holds and three preempts) to override normal controller operation to progress detected platoons. The system deduces the red status of signal phases from the green and yellow contact closure signals that are received from the back panel. The logic assumes phase status to be red if an enabled phase is not green or yellow.

In TS-1 cabinets the CCI module checks the status of the phases and stopbar detectors every 15-20 milliseconds. The CCI module uses the contact closure information received through the NI-DAQ card to determine the status of each phase (green/yellow/red) and stopbar detector status (on/off) and makes the information available to the rest of the PIA system software modules. The CCI module also checks the status of each detector in the advance detector traps and passes the information to the SC module, which calculates speed and length of each detected vehicle once it clears the trailing detector of a trap. In this configuration, timer relays can be used to provide fail-safe operation. When installed, such a timer relay terminates a hold or preempt signal passing through it any time it continues beyond a user-specified maximum time.

TS-2 Cabinets

There are two options for installing the PIA system in TS-2 cabinets:

- Option 1 is similar to the one described in the previous subsection and requires the installation of a TS-2 to TS-1 conversion panel. This option requires NI-DAQ card(s) to obtain phase and detector status information via contact closure connections.
- Option 2 uses enhanced BIUs that provide the PIA system with an RS-232 serial interface to information it needs from the traffic controller cabinet. In this option, information is sent and received from the controller cabinet via messages through the RS-232 serial interface provided by the enhanced BIUs. However, it requires replacement of the existing BIUs with up to five enhanced BIUs (BIUs 1, 2, 3, 4, and the detector BIU 9). In case the existing BIU rack in the cabinet has only two slots (for BIUs 1 and 2), an additional auxiliary BIU rack will be needed to install BIUs 3 and 4.

Figure 9 provides an illustration of an enhanced BIU. Notice the additional RS-232 serial port on the front.

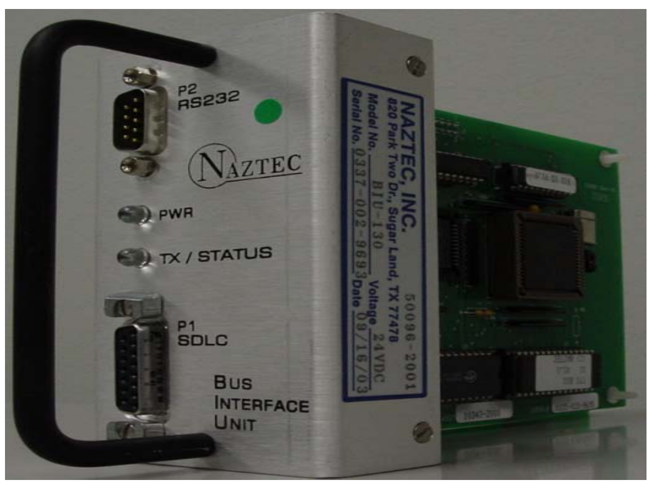

Figure 9. TS-2 Cabinet Enhanced BIU.

The CCI module communicates with the controller through the enhanced BIUs via serial messages every 100 milliseconds. The CCI module deciphers the serial messages to determine the status of phases and detectors. This module also sends any controller override commands through such messages. It retrieves the phase status and the stopbar detector status information from BIU 1 and BIU 9 (detector BIU), respectively. Furthermore, it transmits phase hold and preempt activation commands to the controller through BIU 3 and BIU 2, respectively. The CCI module needs BIU 4 in cases where the phase check input is required for phases instead of the stopbar detector status.

Platoon Detection Module

The PD module in PIA-2 uses the same platoon detection and extension algorithm as used by the PIA-1 system. Chapter 1 provides a description of this algorithm. However, the software code for the PD module had to be redesigned and rewritten to enable algorithm application for two approaches. The module receives per-vehicle speed, length, and lane identification information from the advance detector through the SC module.

Platoon Scheduling and Progression Module

As in the PIA-1 system, the PSP module uses real-time phase status, stopbar detector status, and platoon detection information for each main-street phase to make platoon progression decisions. However, researchers had to completely redesign and recode the PSP module to accommodate a complex matrix of schedules possible when dealing with the progression of up to two opposing platoons. In the process, they enhanced the system to include controller override via phase holds. To progress a platoon, the program can now exercise controller override via three options:

1. phase holds only,
2. low-priority preempt only, or
3. a combination of low-priority preempt followed by phase hold.

Option 1 is the least intrusive and takes control to progress platoons only when the subject phase is green. As such, it guarantees that the platoon phase does not terminate due to demand on a nonpriority phase while a detected platoon is being progressed. When enabled, the program uses preemption to switch the platoon phase from red to green. Under Option 2, the program continues to use preemption until the override termination condition becomes true. Under Option 3, the program operates as follows:

- If the platoon phase is red, it issues a preemption signal. As soon as the subject phase becomes green, the program places a hold signal and removes the preemption signal, ensuring continuity of controller override.
- If the platoon phase is green, the program places a hold.

It should be noted that the removal of a phase hold signal provides snappier termination of controller override than the removal of a preemption signal. Thus, Option 3 is more desirable than Option 2.

During in-lab testing of the PIA-2 system using hardware-in-the-loop (HITL) simulation, researchers noticed that removing the low-priority preempt signal also removed the hold signal placed just prior to its removal. Trial and error revealed that the preemption and hold control sequence worked as intended with high-priority preemption. Therefore, they decided to use high-priority preemption. One negative consequence of this change was that PIA-1's method of using ring status bits plus phase on information could no longer be used to determine real-time phase status. Thus, researchers modified the logic to directly obtain the status of green and yellow signals. PIA-2 logic uses this information to deduce the status of red signals.

To provide the best handling of different scenarios or cases, the PSP uses combinations of two phase holds and three high-priority preempts. Researchers recommend preempts 4 and 5 for individually controlling phases 2 and 6, and preempt 3 when both main-street phases (2 and 6) need to be controlled simultaneously. A complex matrix is required to describe all possible scenario combinations, which depend on phase status, platoon(s) detected or in progress, and constraints placed by demand level on privileged phases. The following list identifies different cases assuming that preempt 4 activates phase 2 only, preempt 5 activates phase 6 only, and preempt 3 activates both phases 2 and 6:

- If a platoon is to be progressed on phase 2 (6) only, and this phase is red, PSP activates preempt 4 (5). Once phase 2 (6) changes to green, the PSP places a hold on this phase and drops the preempt.
- If a platoon is to be progressed on phase 2 (6) only, and this phase is green, the PSP places a hold on this phase.
- If platoon progression is needed on both phases and both phases are green, the PSP places holds on both phases.
- If platoon progression is needed on both main-street phases and at least one main-street phase is red, the PSP activates preempt 3. Once both main-street phases are green, the PSP places preempts with holds on both phases.

Note that the user has flexibility to specify which preempts call which phases. For instance, the software allows phases 4 and 8 to be the main-street phases. The only requirement is the common preempt that activates both main-street phases be a lower number than the individual preempts.

PIA-2 HARDWARE REQUIREMENTS

Figure 10 shows the hardware architecture of the PIA-2 system. Comparing it with the PIA-1 architecture (Figure 1) reveals the following differences:

- as desired, the hardware classifier has been replaced by a software classifier, which also provides the capability to interpret serial messages from a smart sensor, and
- the system has been enhanced to provide a serial interface with TS-2 cabinets, while retaining its ability to communicate with a TS-1 cabinet.

As shown in Figure 10, the system supports several different hardware configurations, which range from all analog (wired) communication to fully serial communication between the PIA-2 system and field hardware. The PIA System User and Installation Guide [*6*] provides detailed information about PIA hardware components and their procurement specifications.

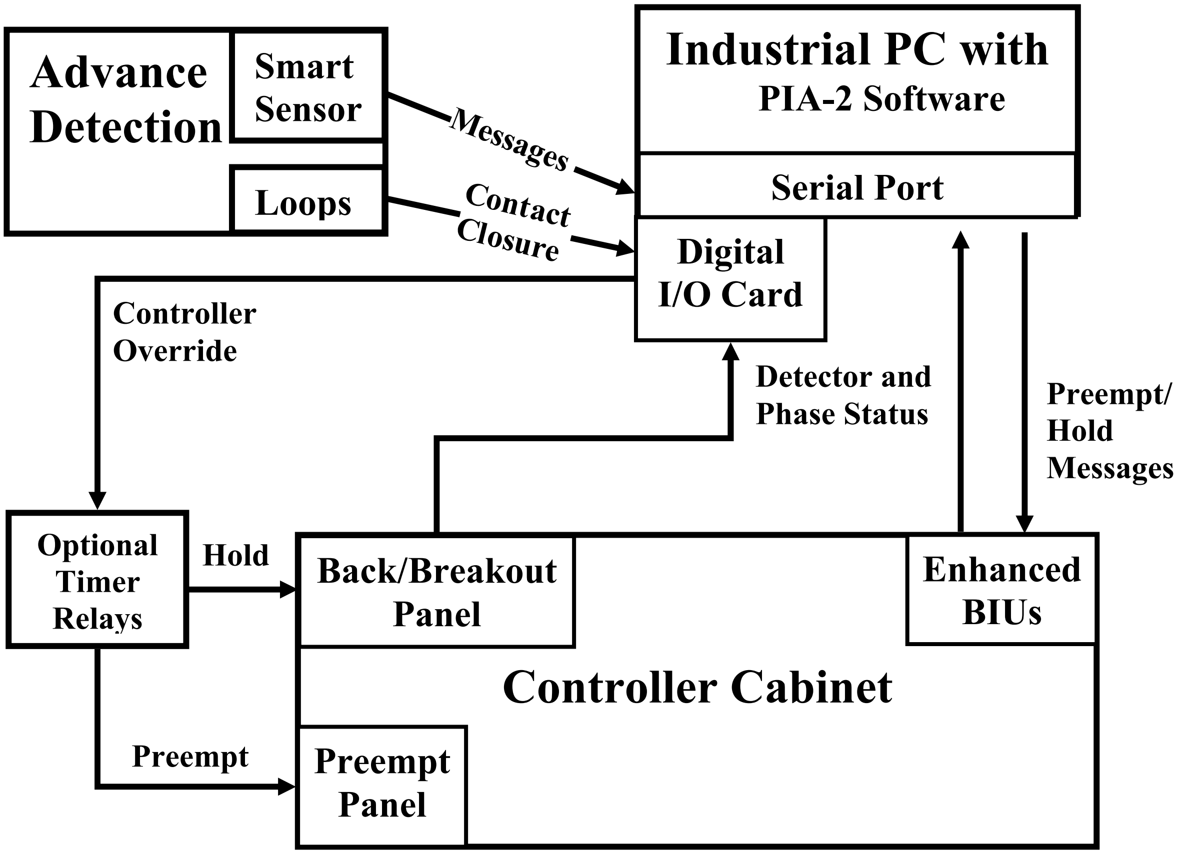

Figure 10. PIA-2 Hardware Architecture.

SYSTEM DEVELOPMENT AND TESTING

During the development of a complicated system like PIA-2, it is essential to conduct in-lab testing of individual system components as well as the entire system. Such testing uses a controlled environment to ensure that the system is working as intended. HITL simulation provides such an environment. A more sophisticated form of HITL simulation is cabinet-in-the-loop (CITL) simulation, which provides the capability to test the entire system as implemented in a field cabinet. CITL simulation provides full replication of field hardware. However, because it uses simulated traffic, the CITL setup provides system testing without jeopardizing the safety of motorists. Researchers had developed and extensively used a TS-1 cabinet-based CITL simulation for testing the PIA-1 system [*1*]. As illustrated in Figure 11, the brain of this system is CITL software, which provides an interface to the cabinet and simulation software. To accomplish the objectives of this project, researchers prepared another signal cabinet to allow use of the same CITL software with a TS-2 cabinet. This adaptation required the installation of a break-out panel to provide communication between the CITL software and the cabinet. During various stages of PIA-2 development and testing, researchers made extensive use of CITL using both TS-1 and TS-2 cabinets. This testing ensured that the PIA system's new communication logic using serial interface to the BIUs worked as intended, while retaining the software's ability to communicate with a TS-1 cabinet via a digital card in the computer.

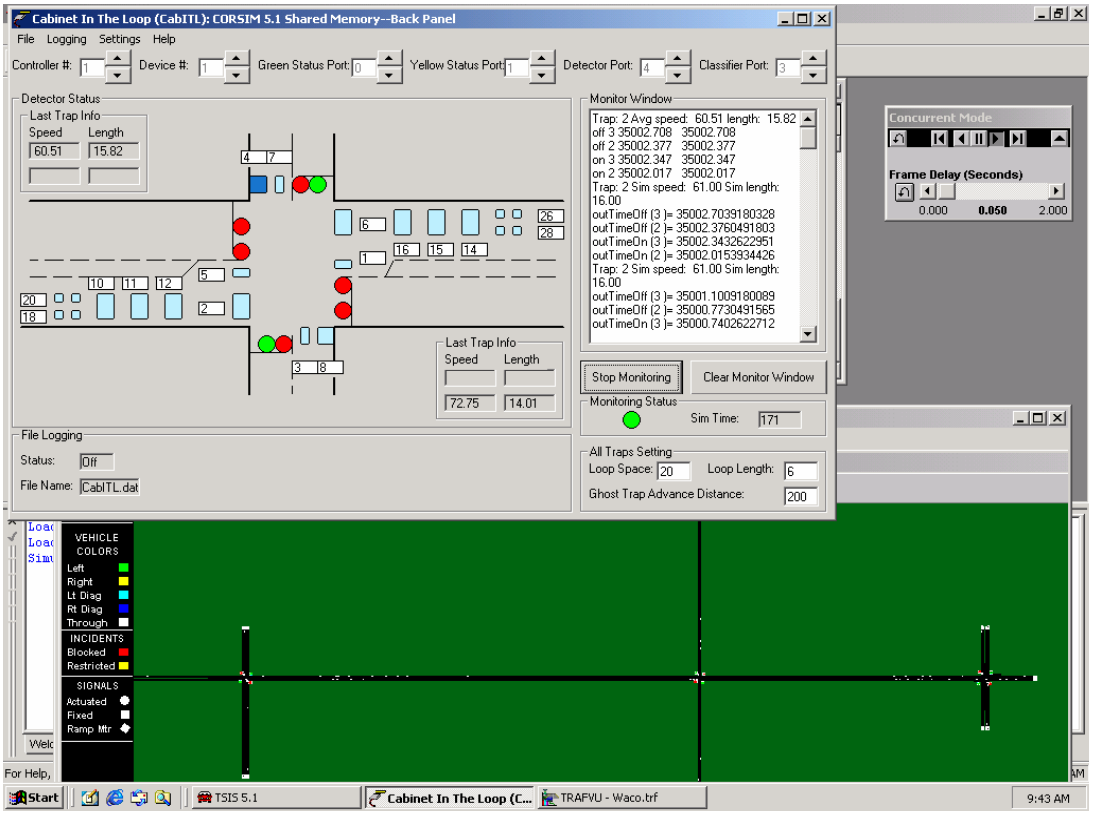

Figure 11. Illustration of Cabinet-in-the-Loop Software.

3. FIELD EVALUATION OF THE PIA-2 SYSTEM

Researchers field-tested the enhanced PIA system at two sites. This chapter describes work conducted by researchers during field installation and evaluation. It also provides results of the field evaluations.

SITE SELECTION

The PIA-2 system was developed to improve traffic operations at isolated traffic signals that:

- are located near adjacent signals on the arterial or highway,
- face widely varying and unpredictable traffic demands throughout the day, and
- receive a significant number of vehicular platoons on one or both arterial/highway approaches during the course of a normal day.

Thus, the two selected sites must meet these geometric and traffic conditions, while providing the means to test the new features of the PIA-2 system to the maximum extent possible. It was also desirable to select sites that do not require a significant number of overnight trips, and where TxDOT could install advance detection in a timely manner. During the early stages of this project, researchers selected FM 2818 at George Bush Drive in College Station, Texas, as one of the two implementation sites. This site was desirable because it:

- met the geometric and traffic criteria for installing the PIA-2 system,
- is located a few miles from TTI headquarters, and
- had an operational AWEGS system, providing two potential benefits:
  - all necessary infrastructure, including advance detection, additional cabinet, and all hardware for installing the PIA system was already in place, and
  - if needed, the means to test the PIA-2 with advance warning capability was available.

To select the second site, researchers evaluated four additional intersections located within 100 miles of TTI headquarters. These intersections are:

- SH 317 at FM 439 in Belton,
- SH 21 at High School Access in Caldwell (T-intersection),
- FM 1695 at FM 2063 in Hewitt, and
- US 85 at Wal Mart in Mexia (T-intersection).

To determine which site was best suited for the needs of this project, researchers made scouting trips to each of the four sites and gathered the following preliminary data:

- features of surroundings:
    - posted and operating speeds at approaches to the subject intersections,
    - distance to adjacent signal(s), and
    - other relevant features.
- geometric data at the intersection, including:
    - number of approach lanes on each leg,
    - lengths of any turn bays, and
    - other geometric features and level of surrounding development.
- inventory of traffic control infrastructure, including:
    - locations and sizes of detectors,
    - number and types of signal heads,
    - type, location, and interior space availability of signal cabinet, and
    - type of signal controller.
- traffic operations data for peak and off-peak periods, including:
    - observation and video taping of traffic demand/flow, and
    - signal operation.

None of these sites had adjacent signals on both sides. After evaluating preliminary data, researchers selected the intersection of SH 317 and FM 439 in Belton as the second field implementation site. The primary reasons for rejecting the other sites are provided below:

- The intersection in Mexia provides access to a shopping facility. During an entire day of observations at this site, researchers did not observe any significant platoons on the main-street approaches.
- The intersection in Caldwell was a good candidate, but it was not possible for TxDOT to install inductive-loop-based advance detection at this site in a timely manner. Arrangements were made for a wireless video detection system. However, an obstruction in the line of sight caused by a large tree on one of the intersection approaches made wireless an infeasible communication option.
- The intersection in Hewitt has an adjacent railway track approximately 250 ft from the intersection on the east side. Present intersection control does not use rail preemption, probably because of this separation. During the visit, researchers observed that the train passage caused the storage space (250 ft) between the intersection and the tracks to fill, blocking all southbound left turns, northbound right turns, eastbound through traffic, and all traffic on the westbound approach. Such conditions are undesirable for PIA system operation.

SYSTEM INSTALLATION AND FIELD STUDIES

Intersection of FM 2818 and Bush Drive

This intersection is located in College Station, Texas, and belongs to the city. Figure 12 shows the subject intersection (circle pointed by the arrow) located on the west end and the adjacent signal (square pointed by the arrow) located on the east end about 1.75 miles away. The other two arrows identify locations of two new signals that became operational soon after this project ended. Figure 13 shows a zoomed view of the subject intersection.

Figure 12. College Station Site and Adjacent Signal.

Figure 13. Zoomed View of College Station Site.

Figures 14 and 15 show features of, and roadway infrastructure at, the two main approaches of this intersection.

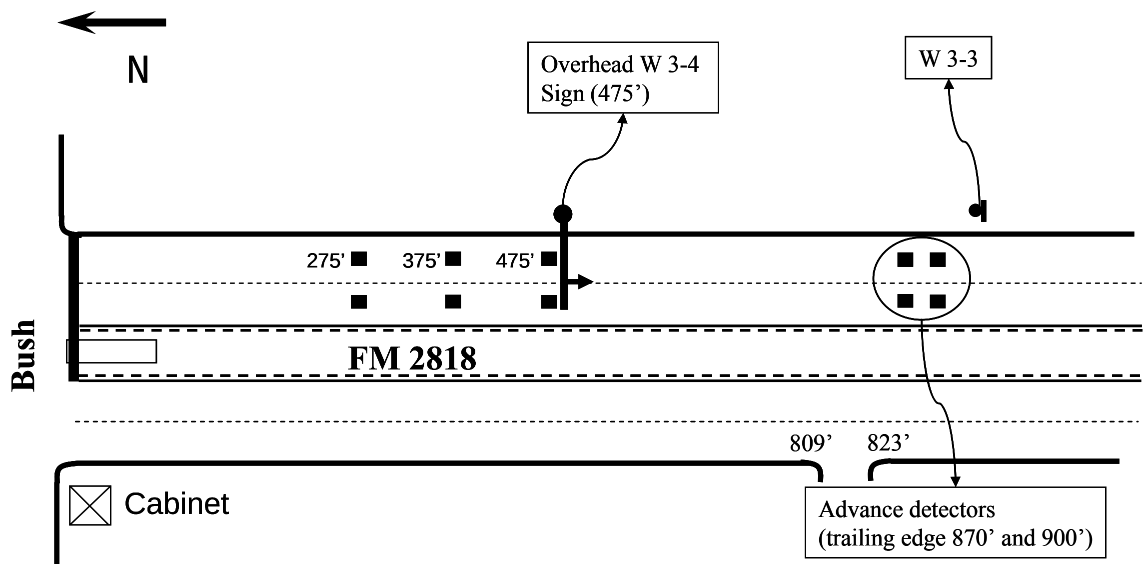

Figure 14. Roadway Infrastructure and Features of Bush Northbound Approach.

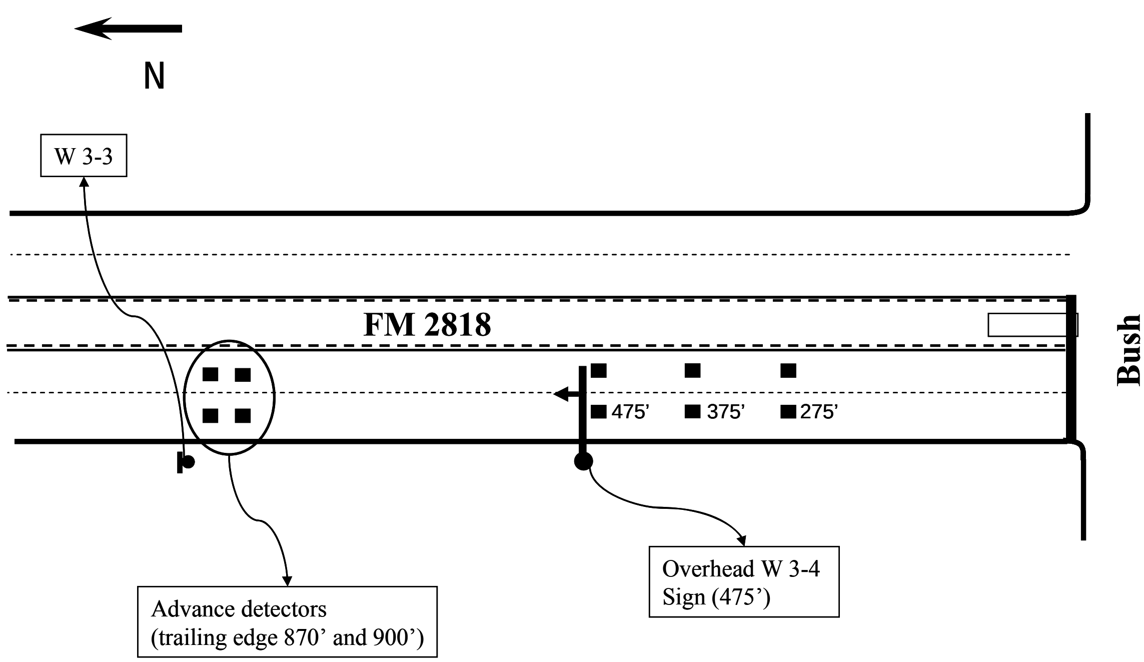

Figure 15. Roadway Infrastructure and Features of Bush Southbound Approach.

The Texas A&M University (TAMU) campus is located north of this intersection, resulting in heavy traffic to and from the campus during AM- and PM-peak periods. During peak times, the through approaches also face heavy demand because FM 2818 provides one of two bypasses around the city. The southwest leg has one approach lane and provides access to additional TAMU system facilities, including a disaster management training facility. Normally, traffic to and from this leg is minimal, but it significantly increases during training courses. Furthermore, each main-street approach has two through lanes and one left-turn bay providing protected permissive left-turn phasing. The Bush Drive approach has one left-turn bay, one left plus through shared lane, and one exclusive right-turn lane. Roadside control hardware is contained in a TS-1 cabinet located in the south quadrant. Figure 16 shows a picture of hardware in the signal cabinet.

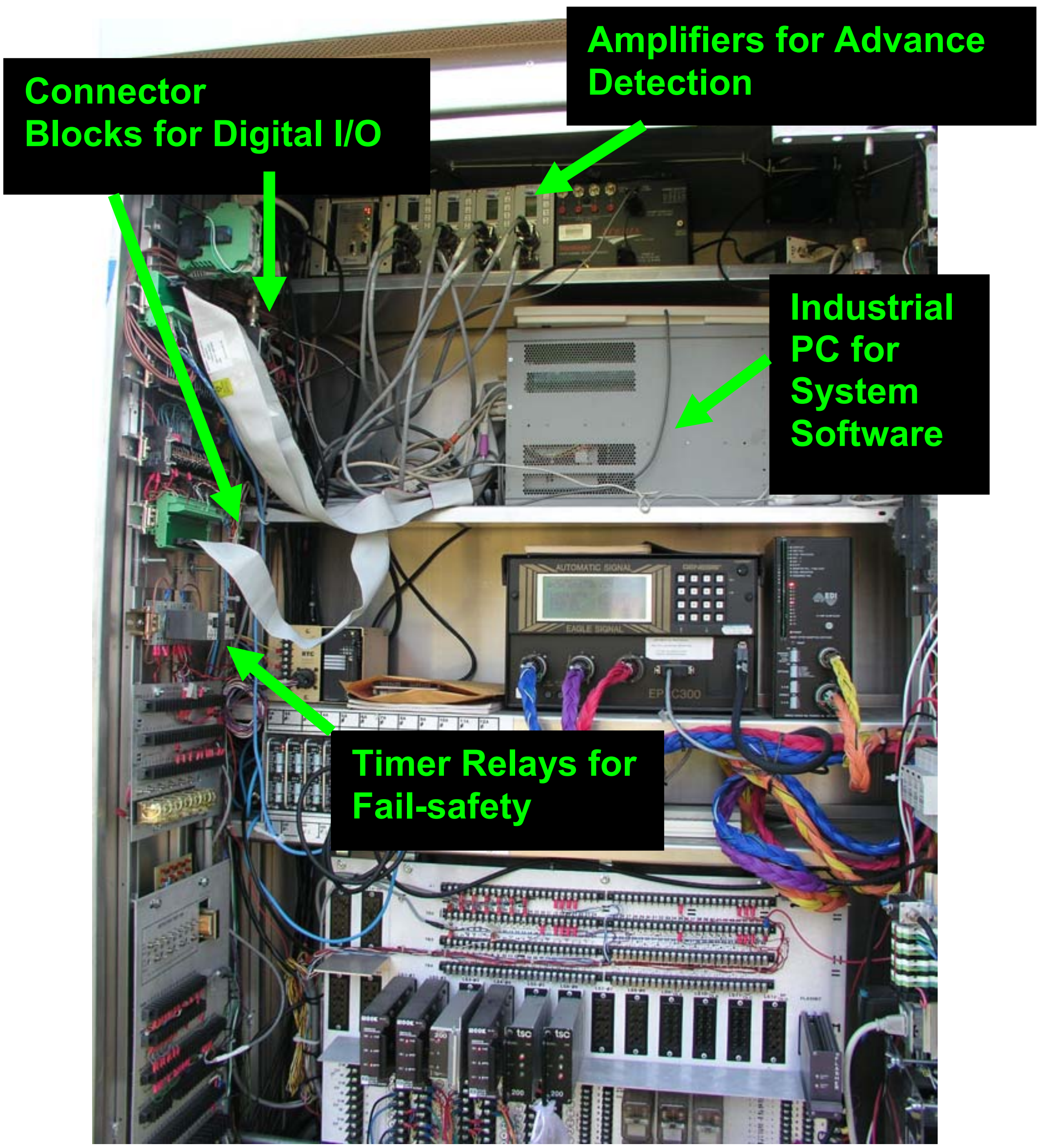

Figure 16. Picture of Signal Cabinet at the College Station Site.

As shown in this figure, this hardware includes an industrial PC for running custom software, loop amplifiers for advance detection, timer relays to provide fail-safe operation, and connector blocks for providing standardized wiring connections. Additional hardware at this site included in-cabinet electronics for advance flashers, roadside advance flashers, and inductive loop detector traps in each of the two through lanes of the main approaches. These detectors are located 1000 ft upstream of the respective stop bars. The advance detectors are located upstream of standard dilemma zone detectors. This site has posted approach speeds of 60 mph in both directions.

PIA installation at this site was completed on August 23, 2007, by conducting the following sequence of tasks:

1. installing the PIA system software on the PC,
2. shutting down the AWEGS system, which switches the advance flasher to backup mode,
3. increasing counter times on timer relays,
4. configuring the system, including controller override via phase holds only, and
5. turning on the PIA system.

Shutting down of AWEGS was necessary to test the PIA system because it was not possible to run the two programs concurrently. However, no changes to wiring were necessary for PIA system installation because the new software design and development process ensured compatibility between AWEGS and PIA system designs. Furthermore, researchers had to limit system testing duration because of safety concerns raised by turning off the AWEGS system, which local drivers had become accustomed to. Program testing, conducted during the next few days, showed that the PIA system worked as intended. This test succeeded because the system had been extensively tested at the Belton site, described below, before installation in College Station.

Intersection of SH 317 and FM 439

This T-intersection (Figure 17) is located in Belton and is maintained by the TxDOT Waco District. At this intersection, signal phase 2 serves two through lanes of outbound traffic arriving from an upstream signal (also a T-intersection) located approximately 1300 ft away. The outside lane in the northbound direction drops approximately 700 ft north of the subject intersection. Left-turn traffic on the northbound approach is served by a protected plus permissive phase (Ø). Phase 5 serves the protected portion and leads the opposing through phase. The southbound approach, served by Ø6, has one through lane and no upstream signal. This approach frequently experiences platoons formed due to slow-moving vehicles. A T-intersection exists to the west on FM 439 approximately 3500 ft away. A school located in the southwest quadrant of this intersection is a major source of to/from traffic in the morning and late afternoon peak periods. From 7:00 AM to 7:45 AM, heavy school-bound traffic is composed of northbound left turns and southbound free right turns, which are 50 percent of southbound demand. As shown in Figures 18 and 19, the eastbound approach (phase 4) faces heavy demand during 3:45 PM to 4:15 PM on weekdays, causing several back-to-back phase failures.

Figure 17. Map of Belton Site.

Figure 18. Heavy Traffic on Eastbound Approach Served by Phase 4.

Figure 19. Heavy Bus Traffic on Phase 4.

Other traffic characteristics at this site include:

1. heavier inbound through traffic during AM peak,
2. heavier outbound through and left-turn traffic during PM peak, and
3. widely varying traffic demand, including significant truck traffic, on all approaches throughout the day.

The existing TS-1 cabinet at this site did not have any room for additional equipment. Therefore, TxDOT staff installed an auxiliary cabinet by securing it to one side of the existing cabinet (see Figure 20), and drilled a hole across to provide for wiring. In addition, TxDOT arranged for installation of advance detectors. The installation provided separate cables from each detector to the auxiliary cabinet via existing conduits running to the main cabinet. Figures 21 and 22 show the locations of these detectors. These figures also show other features of inbound and outbound approaches at this intersection. TTI researchers installed a connector panel and wired it to the main signal cabinet and advance detectors. The other ends of the wires from this panel connect to a PC via a digital I/O card. The PIA software resides on this PC. Figure 23 shows all equipment installed in the auxiliary cabinet. Note that the wireless router and Autoscope unit were installed for temporary use, which included remote monitoring of the system during the initial period and collection of additional data for evaluation purposes.

Figure 20. Additional Cabinet Installed for the PIA-2 System.

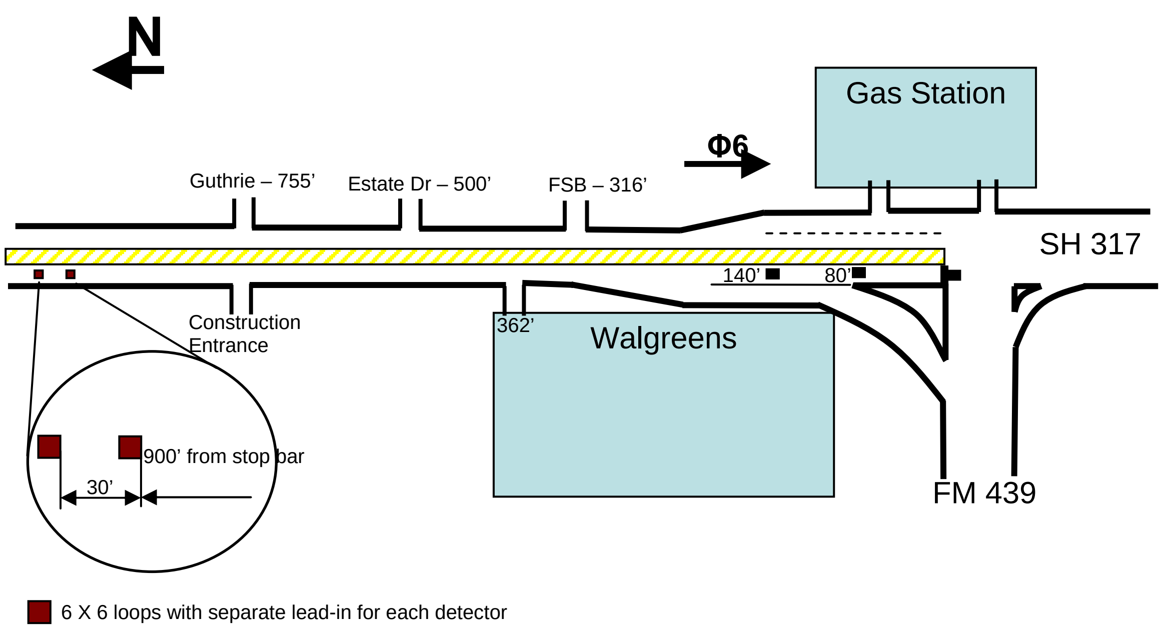

Figure 21. Features of Inbound Approach at Belton Site.

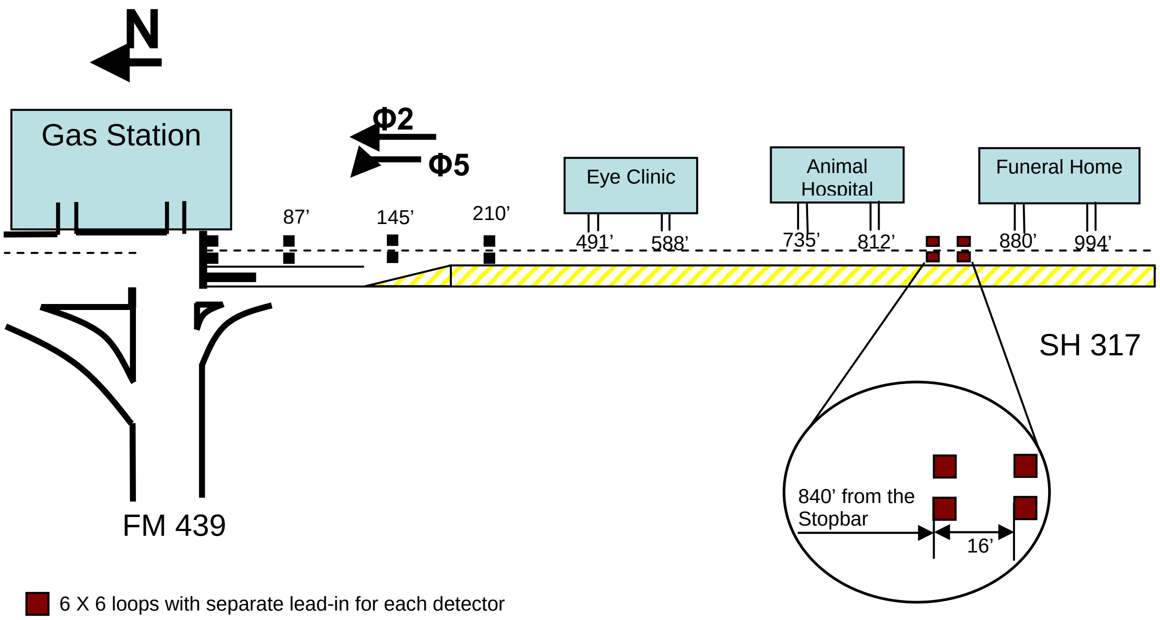

Figure 22. Features of Outbound Approach at Belton Site.

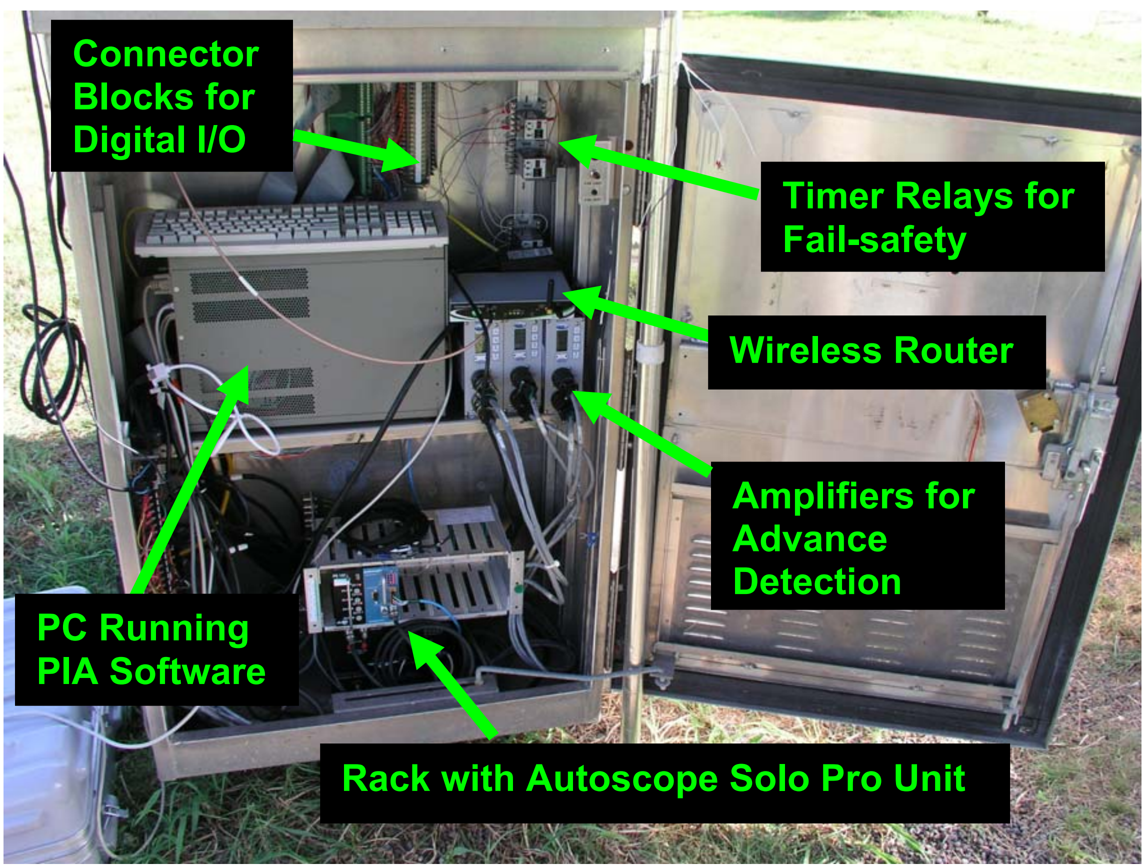

Figure 23. Inside View of Additional Cabinet after System Installation.

Figure 24 shows the controller ring-barrier structure and existing minimum and maximum times for phases at this site.

	Barrier 1		Barrier 2
Ring 1	Ø2 (10, 30)		Ø4 (8, 25)
Ring 2	Ø5 (5, 20)	Ø6 (10,40)	

Figure 24. Ring-Barrier Structure.

Researchers turned on the full PIA system operation at this site on August 8, 2007. For several weeks prior to that, researchers operated the system in shadow mode. In this mode, the system collected all data and performed all computations but did not exercise control to progress platoons. During the August 8, 2007, site visit, researchers connected the output wires from the digital card on the PC to the controller through the "D" connector. Researchers also made the following changes to the timing parameters in the controller:

- programmed preempts 3 and 4 in controller,
- changed Max 1 for phase 4 from 25 seconds to 40 seconds,
- changed Max 1 on phase 5 from 20 seconds to 30 seconds, and
- changed passage time on phase 5 from 1.5 to 2.0 seconds.

Preempt 4 was programmed to progress platoons on phase 2 only, while preempt 3 (which has higher priority than preempt 4) was used to progress platoons on phase 2 only and simultaneous platoons on phases 2 and 6. As mentioned earlier and illustrated in Figures 18 and 19, phase 4 experienced cycle failures during some times of the day. This observation indicated the need to increase the Max time. Also, researchers anticipated that platoon progression, especially on phase 6, will result in increased red times for phases 4 and 5. Researchers increased Max times for these phases to prevent any resulting cycle failures on these phases. Researcher also changed passage time on phase 5 to eliminate premature gap-out observed in the field. Table 1 shows the refined PIA system operating parameters. Data collected while the system was running in shadow mode were used to select these values. A demonstration of PIA operation to members of the TxDOT Advisory Panel was given on August 24, 2007.

Table 1. Refined PIA Algorithm Parameters.

	Phase 2	**Phase 6**
Preempt Max (seconds)	65	65
Initial Platoon Size (vehicles)	6	6
Cumulative Headway (seconds)	18	18
Average Headway Threshold (seconds)	2.5	2.5
Extension Threshold (seconds)	3	3
Pre-estimated Arrival Time (seconds)	0	3
Post-estimated Arrival Time (seconds)	2.5	2.5

Maximum delay on privileged phases 4 and 5 was set equal to 7 and 0 seconds, respectively

Comparison of Before and After Data

At the College Station site, researchers could not operate the PIA system for a long enough time to collect meaningful before and after data. However, researchers were able to collect more than enough before and after data from the Belton site. This subsection summarizes analysis results for five consecutive days (from Friday through Tuesday) during the before period and the same five days during the after period. Before and after data are from August 3, 2007, through August 7, 2007, and August 17, 2007, through August 21, 2007, respectively. As such, the data sets include two weekend days and three weekdays. Tables 2 through 8 summarize the results of analysis of daily (24 hour) data for the five selected days. Observations from these tables follow.

Table 2. Main-Street Counts Measured Using Advance Detectors.

		Friday	Saturday	Sunday	Monday	Tuesday
Phase 2	Before	9896	7932	6925	8574	8661
	After	9889	8371	7148	8915	9003
	% Change	0	6	3	4	4
Phase 6	Before	8049	6531	5728	7445	7347
	After	8338	6901	6042	7714	7851
	% Change	4	6	5	4	7

Table 3. Number of Before and After Signal Cycles for Various Phases.

		Friday	Saturday	Sunday	Monday	Tuesday
Phase 2	Before	1027	1019	910	1009	1033
	After	937	942	848	895	919
	% Change	-9	-8	-7	-11	-11
Phase 4	Before	1027	1020	909	1010	1032
	After	908	901	817	867	888
	% Change	-12	-12	-9	-14	-14
Phase 5	Before	879	861	774	840	861
	After	653	706	636	640	658
	% Change	-26	-18	-18	-24	-24
Phase 6	Before	1429	1497	1364	1385	1412
	After	1240	1335	1234	1210	1235
	% Change	-13	-11	-10	-13	-13

Table 4. Before and After Utilization of Phase 2.

Phase 2		Friday	Saturday	Sunday	Monday	Tuesday
Before	>Max	66	64	61	61	60
	Max	3	2	4	4	3
	>Half	15	16	14	18	17
	<Half	10	11	11	11	12
	Min	6	6	9	7	8
After	>Max	70	68	70	68	67
	Max	3	3	3	4	3
	>Half	14	14	12	14	15
	<Half	8	10	10	8	8
	Min	5	5	5	6	6

Table 5. Before and After Utilization of Phase 4.

Phase 4		Friday	Saturday	Sunday	Monday	Tuesday
Before	>Max	0	0	0	0	0
	Max	2	0	3	2	2
	>Half	11	4	3	10	9
	<Half	40	35	30	41	43
	Min	48	60	64	47	46
After	>Max	0	0	0	0	0
	Max	0	0	0	0	1
	>Half	4	1	1	4	6
	<Half	52	44	42	53	52
	Min	40	51	54	39	38
	<Min	3	3	3	3	3

Table 6. Before and After Utilization of Phase 5.

Phase 5		Friday	Saturday	Sunday	Monday	Tuesday
Before	>Max	0	0	0	0	0
	Max	4	1	2	2	3
	>Half	12	5	3	11	10
	<Half	32	33	30	35	35
	Min	51	61	65	52	52
After	>Max	0	0	0	0	0
	Max	0	0	0	0	0
	>Half	2	1	0	2	2
	<Half	46	42	35	45	46
	Min	51	56	65	53	52

Table 7. Before and After Utilization of Phase 6.

Phase 6		Friday	Saturday	Sunday	Monday	Tuesday
Before	>Max	15	17	20	15	14
	Max	2	21	1	2	2
	>Half	20	15	16	17	16
	<Half	47	48	42	46	47
	Min	16	18	20	20	22
After	>Max	32	27	33	31	29
	Max	3	2	2	3	2
	>Half	18	16	16	17	17
	<Half	33	41	35	34	37
	Min	14	13	14	14	14

Table 8. Platoon Detection Statistics.

		Friday	Saturday	Sunday	Monday	Tuesday
Phase 2	Detection	540	403	314	488	446
	Hold	198	190	164	200	178
	Preempt (#)	173	131	101	152	156
	Hold+Preempt	371	321	265	352	334
	% Progressed	69	80	84	72	75
	Extension 1	1124	750	541	1089	989
	Extension 2	1635	1128	824	1490	1339
	% Demand	50	45	41	53	48
Phase 6	Detection	424	263	194	358	365
	Hold	65	69	58	72	68
	Preempt (#3)	134	87	64	100	111
	Hold+Preempt	199	156	122	172	179
	% Progressed	47	59	63	48	49
	Extension 1	746	531	426	773	689
	Extension 2	1088	718	631	1028	974
	% Demand	36	32	30	37	35

A comparison of before and after counts (Table 2) from advance detectors show a slight increase between the two analysis periods, which are about 10 days apart. Except for phase 2 (outbound/northbound direction) on Friday, the increase ranged from 3 to 7 percent. It is unlikely that these changes were random. Because the first day of classes at the nearby high school was August 27, 2007, this increase was not because of normal school traffic. However, it may be due to the end of summer and school staff activities.

Table 3 provides before and after analysis of the number of cycles for all four phases at the intersection. The reader will notice that in general, the number of cycles for all phases decreased after the PIA system was turned on. There are two reasons for this change. The first and obvious reason is the increase in Max times for phases 4 and 5 implemented on August 8, 2007. The second reason is controller override for platoon progression, which may extend green beyond a platoon (main) phase's Max time in the presence of demand on conflicting phases. The reader should note the following points about these data:

- In the before case, phases 2 and 4 have the same number of cycles as they should. However, in the after conditions, there is a discrepancy between the two numbers. The reason for this discrepancy may be that phase 2 started terminating and was brought back by PIA override to progress a detected platoon. However, researchers have not been able to identify the exact reason, which may require more detailed analysis of recorded controller events and/or in-field observations.
- The maximum decrease in the number of cycles was noticed for phase 5, which is the protected portion of a protected plus permitted phase serving northbound arterial left turns. The most probable reason for this decrease is increased permissive phase capacity due to the increase in the length of phase 6 green due to PIA override of the controller.

Tables 4 through 7 provide before and after green phase utilization as a percent of total number of cycles per day. It should be noted that the numbers in the columns do not always add to 100 percent because of rounding to whole numbers. The categories of data include percent of total cycles the phase green was:

- greater than phase maximum (>Max),
- equal to phase maximum (Max),
- greater than 0.5 × (Max - Min) + Min, but less than Max (>Half),
- less than 0.5 × (Max - Min) + Min, but greater than phase minimum (<Half),
- equal to phase minimum (Min), and
- less than phase Min.

The first condition is only true for a main-street phase under two conditions:

- phase dwells in the absence of demand on conflicting phases, or
- phase green extension beyond Max due to PIA system override.

The last condition applies only to a minor phase when it is terminated by PIA override before serving Min green. This condition is not desirable and should be eliminated. The following additional points should be noted from these tables:

- For main-street phases, the >Max percentages increased. For phase 2, this increase is minor because concurrent phases 5 and 6 frequently override the rather small Max time for this phase. In addition, phase 2 dwells in green during a significant part of the day due to no demand at the only conflicting phase (phase 4). For phase 6, the increase in >Max is significant (13 percent).
- For phase 4, the number of Max times decreased to zero, but <Half values increased by about 10 percent. At the same time, Min greens decreased by similar

percent. These results are due to increased Max time for this phase and the aggregation of more vehicles served during each cycle. From these data, researchers concluded that the increase in Max times was not warranted for the conditions. It should be noted, however, that the phase failures that led the researchers to increasing Max times were observed before schools were closed for the summer of 2007. Thus, it is premature to make any conclusion about the appropriateness of new Max times without analyzing data from a period after August 27, 2007.

- For phase 5, there is a shift between >Half and <Half, and the number of Max was decreased to zero. Again, the appropriateness of revised Max times should be checked using the data after school started.
- In the after case, phase 4 terminated before serving the Min green during 3 percent of cycles. This condition is of concern because of safety reasons, and should be prevented by making appropriate modifications to the PIA-2 system.

Table 8 provides platoon detection and progression statistics for phases 2 and 6. These statistics include: platoons detected, platoons progressed using holds, platoons progressed using preempts, total platoons progressed (Hold + Preempt), percent of platoons progressed, platoon progression extended due to T_h (average headway threshold) and T_e (last vehicle in the platoon threshold) criteria, and percent of observed approach demand (% Demand) that benefited from the PIA-2 system. These data provide the following information:

- On phase 2 (phase 6), the system detected 314 to 540 (194 to 424) platoons during the five days.
- Additional calculations (not shown here) reveal that the number of platoons on phase 6 ranges from 62 percent to 82 percent as compared to phase 2. This is a surprising finding because phase 6 has no upstream signal.
- For phase 2 (phase 6), 69 to 84 (47 to 63) percent of detected platoons were progressed. This result is expected because phase 2 was constrained by demand on only one privileged phase (phase 4), while phase 6 was constrained by demand on privileged phases 4 and 5. Also recall that phase 5 demands were served without any delay.
- The system ensured the progression of 41 to 53 (30 to 37) percent of total observed demand on phase 2 (phase 6). Note that this calculation uses total observed demand provided in Table 2. The total number of vehicles that benefited from platoon progression was calculated by multiplying the number of progressed platoons by 6 (minimum number of vehicles for platoon detection) and adding the number of extensions due to the two extension criteria. It should also be noted that these vehicles were also guaranteed dilemma zone protection.

These results demonstrate that the PIA-2 system provided significant benefits to traffic at the Belton intersection. The data also revealed the need to make a few minor modifications to ensure driver safety.

4. CONCLUSIONS AND RECOMMENDATIONS

The objective of this project was to make several enhancements to the original platoon identification and accommodation system developed in a previous project. Furthermore, project objectives included testing the enhanced system at two sites. The system was installed and tested at two sites; however, additional field deployments are needed to exercise the full system capabilities. The required enhancements included:

- addition of a software classifier to replace the hardware classifier used by the PIA-1 system,
- system enhancement to provide standardized installation in TS-2 cabinets, and
- system enhancements to provide platoon identification and accommodation functionality for both arterial directions.

From the developmental complexity point of view, the first two enhancements were straightforward. However, the third enhancement was much more complex. Researchers used cabinet-in-the-loop simulation for incremental in-lab testing of the PIA-2 system; however, full testing of the entire system was conducted in the field.

Researchers field-tested the software classifier module by running the PIA-2 system in shadow mode. They conducted this testing in Belton, Texas. The first step of this testing verified that the software classifier was detecting individual vehicles correctly at both detectors of the advance detector trap. The second step verified that the software classifier was correctly calculating the speeds and lengths of vehicles in each lane. Researchers verified speed calculations using a radar gun and by driving a test vehicle of known length back and forth over the advance detectors in both directions. The latter method verified length calculations against the known length of the test vehicle. In addition, researchers used engineering judgment to verify that the lengths of individual vehicles calculated by the classifier can be used to differentiate between automobile and truck traffic. Because the PIA-2 system does not use vehicle classification information at this time, researchers did not conduct an in-depth evaluation of the software classifier's ability to identify different classes of vehicles.

Testing of TS-2 standardization features could be conducted only in the lab because both selected field test sites had TS-1 cabinets. This testing required verification that the new modules operated as intended, while ensuring that new system's ability to communicate with TS-1 cabinets remained intact. For this purpose, researchers used CITL simulations using TS-1 and TS-2 cabinets. This lab testing was successful.

As stated earlier, extending the system to provide functionality in both arterial directions was extremely complex, requiring reengineering of the entire PIA-1 software. During this reengineering, the only module that primarily remained intact was the core platoon detection algorithm code. During reengineering, researchers modified its code to accommodate one or two directions on the arterial. The most difficult part of the process was identifying and accommodating different combinations of platoon arrivals on two approaches and devising a mechanism that efficiently exercised control to achieve platoon progression under various scenarios. The scheme devised uses up to three low-priority preempts. Two of these are used to provide platoon progression in each direction only, and the third is used to simultaneously provide progression in both directions. The advantage of using preemption is that it uses existing controller features to quickly change a desired phase from red to green. However, inherent sluggishness exists in the resumption of normal controller operation when the preempt signal is removed. To improve efficiency, researchers added the use of phase hold when the signal is already green. In the new control override process, the system places both a preempt and a hold if a desired phase is red. It removes the preempt signal as soon as the subject phase becomes green, making phase hold the active control mechanism. The use of this feature did not work as intended using a low-priority preempt with the controller brand present in both field locations. This new feature worked when the low-priority preempt was changed to a high-priority preempt. However, researchers were forced to revise the software code to obtain real-time phase status from output side rather than ring status bits.

In addition to the required enhancements, researchers replaced the privilege feature of PIA-1, which was static in nature, with a dynamic one. This new feature is adaptive in that it allows the PIA-2 system to modify its platoon accommodation functionality based on traffic conditions on minor phases, but within the constraints established by the user. Adding this adaptiveness feature required researchers to develop code to allow more proactive gathering of real-time data and additional code to process such data into more meaningful or useful information. At present, the system uses real-time information only to tighten or relax constraints on platoon progression to accommodate the levels of demands on minor phases. The system logic can be enhanced to gain additional benefits from real-time information. Such benefits include:

- adaptation of platoon detection parameters to changing traffic demand at various phases. For instance, number of vehicles in the initial platoon and how compact it is can now be dynamically changed based on traffic conditions;
- adaptation to provide preferential treatment to large trucks;
- analysis of platoon arrival history to better accommodate repetitive conditions (i.e., from an upstream signal); and
- adaptive coordination of adjacent signals.

In this project, researchers installed and tested the enhanced system at two sites; however, constraints prevented long-term testing at the College Station site. Furthermore, both locations used TS-1 cabinets and the same brand of controller and had a traffic signal at only one approach. Thus, researchers could only test a subset of program features. Lastly, this project has just scratched the surface in the area of real-time performance evaluation and system adaptiveness because it did not provide an opportunity to perform an in-depth analysis of the wealth of information that can be obtained from the real-time data collected by the PIA-2 system.

Thus, researchers recommend that a follow-up implementation project be initiated to allow:

- testing of features and capabilities that could not be exercised in this project, and
- developing methods to better utilize the wealth of information collected by the PIA-2 system.

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