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High-Speed Rail IDEA Program

Advanced Intersection Controller Response to Railroad Preemption

Final Report for High-Speed Rail IDEA Project HSR-16

Prepared by:
Steven Venglar
Texas Transportation Institute

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IDEA Programs
Transportation Research Board
500 Fifth Street, NW
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Advanced Intersection Controller Response to Railroad Preemption

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Steven Venglar
Texas Transportation Institute

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EXECUTIVE SUMMARY

Signalized highway intersections located near highway-rail grade crossings create a potential safety problem. Since trains approaching a crossing are most likely unable to stop in time to avoid colliding with a vehicle stopped on the crossing, it is necessary to clear vehicles from the tracks before the train arrives. For this reason, traffic signals located near highway-rail grade crossings are interconnected with active warning devices and are programmed to preempt their regular timing sequence and (as quickly as possible) present a green signal to motorists on the intersection approach that crosses the tracks.

The US Department of Transportation (USDOT)/Federal Highway Administration (FHWA) *Manual on Uniform Traffic Control Devices* (MUTCD)(*1*) establishes the traffic engineering standards for all major roadway elements, including the signs, signals, and markings present at highway-rail grade crossings and highway intersections. The MUTCD indicates that signalized intersections within 60 m (200 ft) of a highway-rail grade crossing should be considered for preemption, and that active warning devices shall be active a minimum of 20 seconds before train arrival at the crossing.

Train detection required to initiate active warning device operation at the highway-rail grade crossing is accomplished by the shunting of track circuits by approaching trains. Various technologies are used for track circuits; the more advanced systems in use incorporate train arrival prediction to provide a relatively consistent constant warning time (CWT) regardless of the speed of approaching trains. If the track circuit monitoring equipment is interconnected with a nearby signalized intersection, the preemption provided may be either simultaneous (preempt signal simultaneous with warning device activation) or advance (preempt signal sent to signal controller unit before activation of warning devices), depending on the warning time needs at the adjacent traffic signal.

When traffic signal controllers receive a preempt call, they immediately transfer to a special operating mode to transition out of the active phase(s) and into the track clearance phase(s). When the track clearance begins, vehicles can clear out of the clear storage distance (CSD) between the intersection stop bar and the crossing, and vehicles can move out of the crossing itself. It is not necessary to completely clear vehicles in the crossing through the downstream intersection; the track clearance phase need only be long enough to allow vehicles in the crossing to move out of the crossing, while the activated warning devices indicate that other motorists should not enter the crossing.

The MUTCD allows the signal controller unit a great deal of flexibility in reaching the track clearance phase(s) as quickly as possible. For phases that conflict with the track clearance phase, the minimum phase green time need not be preserved at the onset of preemption. Also, pedestrian WALK times and flashing DON’T WALK times (i.e., pedestrian clearance times) may be abbreviated. In the case of pedestrians, the loss of a full-length clearance interval before the display of the track clearance phase may mean that pedestrians are in the intersection in the path of the vehicles clearing out of the track clearance approach. This possible, though low-probability occurrence is referred to as a “relative hazard” (of pedestrian-vehicle conflict compared to a vehicle-train conflict) by the MUTCD.

Advanced information about train arrival at the crossing is required to affect signal operations in an attempt to avoid the abbreviation of vehicular and pedestrian phasing. This advanced detection time, which would occur even before train detection required for advance preemption, would have to be provided by new detection equipment or by extension of existing track circuitry. Several candidate technologies exist for such detection, including global positioning satellite (GPS), automatic equipment identification (AEI) systems, loop detectors, sonic detectors, radar, infrared and video. Regardless of which technology is used, train speed and the known distance to the crossing would be used to develop an estimated time of arrival for the train at the crossing. This information would then be made available to the logic or controller function to reduce or eliminate the vehicular and pedestrian phase abbreviations.

A logic algorithm, known as the Transitional Preemption Strategy (TPS), was developed in this High-Speed Rail IDEA project as one means of influencing traffic signal controller behavior before the onset of normal, railroad traffic signal preemption. The TPS makes use of advanced train detection information to determine when it should begin affecting phasing sequence and duration at the intersection, with the objective of avoiding phase abbreviations. The TPS was coded into software on a personal computer (PC) and tested in a simulation laboratory. This testing system used an authentic traffic signal controller unit in a “hardware in the loop” simulation environment, where a device known as a controller interface device (CID) transmitted phasing and vehicle detection information between a hybrid TPS/traffic simulation program on the PC and the controller unit. The simulation test indicated the potential of the TPS logic to alleviate phase abbreviation problems, but revealed controller interface issues between the TPS logic and the signal

controller unit. Specifically, it was discovered that when the traffic signal controller unit went into normal railroad preemption, any lingering influences of the TPS on controller operation may not be able to be "turned off," since the signal controller had already transitioned into a special preemption mode. It was also discovered that the TPS may not be able to handle situations where train preemptions are very frequent, since a signal controller may be recovering from a previous preemption when another preemption is initiated, effectively eliminating TPS preparation time for the second train preemption event.

Following the simulation test, a field-based test was conducted of the TPS system. Traffic and train approach data were collected at a field site, and a Doppler radar detection system was used to detect approaching trains before the railroad track circuit's threshold for activation of normal railroad preemption. Data was ultimately available for 51 tests of the TPS logic, each exhibiting unique train warning time, traffic volume, and signal timing characteristics. The data were fed into the same TPS software and CID/controller simulation environment used previously, and 51 "without" TPS and 51 "with" TPS simulations were performed. The results of this field-based simulation test were revealing, not only of the impacts of the TPS on signal operations at the onset of railroad preemption of the signal controller, but also of the impacts of railroad warning time variability on both TPS operation and normal signal preemption.

Warning times were observed to be more variable the farther the time detection horizon was from train arrival at the crossing (i.e., Doppler radar was more variable at an average 70-second detection/prediction horizon than the railroad's CWT equipment, which had a minimum detection/prediction horizon of 35 seconds). In all preemption events, the Doppler radar detection predicted train arrival and, hence, activated the TPS, before the onset of normal railroad preemption. The difference in time between the Doppler advanced warning and the onset of normal preemption was the temporal operating range of the TPS. Where at least 17 seconds of TPS operation time existed, the TPS performed flawlessly, abbreviating neither vehicular minimum green times nor pedestrian clearance times. Adequate warning was provided in 21 of the 51 cases. In the remainder of the cases, warning times were too short to provide full TPS functionality; in some cases the TPS provided at least some degree of benefit in reducing the amount of phase abbreviation, in other cases the TPS had no time to affect controller operation at all. Where advanced warning times were too short, the TPS system made phasing adjustments under the assumption that more time was available before the onset of normal preemption than actually existed. The more this assumption was in error, the greater the negative impact on the effectiveness of TPS operation. Considering the realistic limitations on inherent warning time variability, the TPS could only be deployed in its current form where train speeds were extremely consistent. As this can neither be planned on nor assured in real-world operating environments, the TPS can only be viewed as a developing concept that is not ready for field implementation.

The findings derived from the extended observation and recording of signal preemption events in the field were as significant as the results of the TPS development and test. As both signal operation details and railroad detection and preemption activation details were fully documented in the field, it was possible to observe the impacts of railroad CWT warning time variability on signal operations at the field study site. Where railroad warning times were very long (i.e., the train decelerated within the CWT track circuit), it was physically possible to have the track clearance phase at the intersection terminate before the gate arm at the highway-railroad grade crossing began to descend. This has led to particular interest in the variability of railroad warning times and the impact of this variability on today's signal preemption practices.

A number of awareness and future research needs became apparent during this investigation. Enhancing on the current binary (i.e., on-off) preemption communication protocol between the railroad's CWT equipment and the traffic signal controller unit may minimize variability between the railroad grade crossing predictor and the traffic signal controller. Rather than sending an on-off preempt signal to the traffic signal controller, the grade crossing predictor could send a continuously updated (with steadily improving accuracy) stream of expected train arrival times to the traffic signal controller. This would allow the controller to adapt its preemption sequence to variation in warning times. The TPS algorithm could also be improved to take advantage of such a higher level of information by continuously updating its parameters and decisions based on the expected arrival time of the train at the crossing. In terms of today's preemption practices, procedures and guidelines must be explicitly inclusive of variability issues, especially as they impact the coordination of the beginning and end of the track clearance phase and the operation of this phase with respect to crossing gate operation.

CONCLUSIONS

This research effort resulted in the development of the TPS logic algorithm, a logical process to manipulate traffic signal intersection control before the onset of railroad preemption. Consistent with the objectives of its development, the TPS algorithm was demonstrated in simulation-only environments and field-data based simulations to reduce or eliminate vehicular minimum phase abbreviations and pedestrian clearance abbreviations. While accomplishing these objectives, the TPS did not interfere with the transition of the controller into normal railroad preemption (i.e., at the time the raliroad CWT preemption call was made to the controller unit).

Limitations on the implementation of the TPS include the means of interfacing with the traffic signal controller unit and the inherent variability of railroad warning times. The TPS logic is currently a piece of software code that interfaces with the signal controller unit by means of an external controller interface device. It is the opinion of the research team that the TPS logic would be most efficient and effective if incorporated directly into the software within a traffic signal controller unit. Throughout the TPS testing, issues arose with how the external device (and the TPS logic) would be able to exercise an influence on controller operation (for instance, to remove phase "omits") at and during the operation of the normal railroad preemption routine within the controller unit. Direct incorporation of the TPS algorithm into the controller would eliminate limitations on system effectiveness due to interface issues, and (via the controller manufacturer's development process) ensure compatibility with both the logic and timing of controller functions.

Warning time variability was observed to increase the farther the prediction horizon was from train arrival at the crossing. This limitation exists regardless of how the train was detected (i.e., it is independent of detection technology), as trains can accelerate or decelerate on their approach to the highway-rail crossing. An improvement can be realized if logic algorithms, such as the TPS or the preemption routines programmed into signal controllers, could make use of real time, continuously updating train arrival information. As the train nears the crossing, and, consequently, as the accuracy and reliability of the arrival estimate are improved, more constraints can be placed on controller operation. Means of using such real time information is beyond the scope of this development effort, though there is ongoing research in other areas to develop signal control logic that bases its operation on real time information. Further development and refinement of these systems must take place before they can be considered ready for implementation and, eventually, incorporation of features like the TPS logic.

In its current form, the TPS algorithm would be effective only where train speeds are highly consistent. As it is impossible to guarantee uniform speed in real-world environments, TPS will remain, at least for the time being, in the development stage. The presence of switching operations or the use of the subject tracks by different types of trains (i.e., unit trains, commuter trains, etc.) would certainly preclude TPS system application. Consistent speeds could be enforced by track speed limits, as are commonly imposed to reduce train speed over older rail or within certain communities. However, these restrictions are very political in nature and often not well received by rail owners and operators unless necessary for safety reasons. Unfortunately, such restrictions do not wholly control speeds, as they simply establish an upper bound and would not influence acceleration and deceleration within the detection circuit (as long as the maximum speed were not exceeded).

The data collected during the field study portion of this investigation was extremely useful in aiding researchers in understanding the various processes that occur during railroad preemption. This has led to particular interest in the variability of railroad warning times and the impact of this variability on today's signal preemption practices. Practices and guidelines must be enhanced to be explicitly inclusive of variability issues, especially as they impact the coordination of the beginning and end of the track clearance phase and the operation of this phase with respect to crossing gate operation.

DEVELOPMENT OF THE TPS

Where the paths of any two vehicles meet, it is desired to minimize the number of collisions occurring when one vehicle is often incapable of yielding to the other. At highway-rail grade crossings, the result of such a collision is often deadly due to the large difference in both size and speed of the vehicles involved. While accident rates have been on the decline, the potential for accidents at highway-rail grade crossings has been increasing as a result of higher train and automobile volumes.

One study that examined accidents at highway-rail grade crossings with active warning devices (such as lights and gates), revealed that at least 20 percent of the accidents involved motorists that were stopped on the tracks (*3*). Highway intersections located within 23 m (75 ft) were found to contribute to these accidents. Since trains approaching a crossing are generally unable to stop in time to avoid colliding with a vehicle stopped on the crossing, it is necessary to clear vehicles from the tracks before the train arrives. For this reason, traffic signals located near highway-rail grade crossings are interconnected with the active warning devices and are programmed to preempt their regular timing sequence and present a green signal to motorists on the intersection approach that crosses the tracks to allow them to move out of danger as a train approaches (*4*).

Even when enough time is provided to clear motorists from the tracks, the abrupt interruption of the traffic signal's normal sequence can lead to motorist confusion, inefficient operation on the street that does not cross the tracks, and increased danger to pedestrians. The National Cooperative Highway Research Program's (NCHRP) Synthesis *Traffic Signal Operations Near Highway-Rail Grade Crossings* indicates:

> As more accurate train position information becomes available, traffic signal systems that are adjacent to highway-rail grade crossings could be equipped to accept more detailed data about train position, speed, and estimated time to crossing. With this data, the traffic signal controller would be able to accommodate train movements without the abrupt preemption process, improving highway-rail grade crossing safety and efficiency. (*5*)

In an environment where train approach and estimated arrival time are known and continuously updated up to a minute or more in advance of the train's arrival at the crossing, traffic signal control can be made more efficient and safe. Signal operations would only assign right-of-way to vehicular or pedestrian phases that conflict with the track clearance phase(s) if there exists sufficient time to serve their minimum times and clearance intervals before advancing to fully serve the track clearance phase(s). Developing the controller logic to analyze the adjacent intersection's signal operations and determine the preferred means of serving traffic before, and ultimately advancing to, the track clearance phase was the focus of this research.

MOTIVATION FOR CHANGES TO PREEMPTION PRACTICE

Background

Several existing standards and recommended practices exist to assist the engineer with the design, operation and maintenance of the numerous elements of an active grade crossing warning/interconnected traffic signal system. Roadway standards are given in the MUTCD (*1*), while railway standards are specified in the *Signal Manual* (*2*). The Institute of Transportation Engineers (ITE) publishes its *Recommended Practice for the Preemption of Traffic Signals At or Near Railroad Grade Crossings with Active Warning Devices* (*4*) to guide traffic engineers with preemption design and operation. Also, the FHWA has published a general reference on all aspects on highway-railroad grade crossing features and considerations known as *the Railroad-Highway Grade Crossing Handbook* (*6*), which will soon be updated in a third edition.

Common to the MUTCD (*1*) and the *Signal Manual* (*2*) is the provision of a minimum 20-second warning time of active warning devices at the highway-rail grade crossing before the arrival of a train. This minimum is applied to all crossings without regard to vehicle characteristics, train speed, number of tracks, the existence of an interconnected traffic signal, or other considerations. To provide the indicated minimum warning time of 20 seconds, the railroad's train detection system, or track circuit, will often provide an average warning time more in the range of 25 seconds. In the case of an interconnected nearby traffic signal, which receives a preemption input from the railroad warning device, preemption may be either simultaneous or advance. In simultaneous preemption, the activation of warning devices at the highway-rail crossing is concurrent with the receipt of the preemption call at the traffic signal controller. In advance preemption, the traffic signal preemption input is sent from the railroad warning equipment before the crossing warning devices become active (though maintaining the 20-second minimum warning before train arrival remains).

The minimum warning time required to initiate traffic signal preemption is the sum of the maximum right-of-way transfer time (i.e., from non-track clearance phases to the track clearance phase), the required clearance interval time, and any needed safety buffer time. Without the safety buffer, the calculations assume that the last vehicle stopped on the tracks would clear out of danger just as the train arrives. The *ITE Recommended Practice* (*4*) states that if the calculated minimum warning time exceeds the warning time provided by the railroad train detection equipment, advance preemption should be considered. Advance preemption timings should be based on the worst-case, where the traffic signal controller has the most extensive phasing intervals to transition out of and clear before arriving at the track clearance phase. Consideration should also be made of the best-case scenario, where the signal is already in the phase(s) that will clear vehicles from the tracks (i.e., the track clearance phase) when the preemption input is received. In the best-case situation, it is necessary to adjust phase settings to remove the possibility of queuing vehicles on the track after the track clearance green phase has ended, but prior to the gates being fully in the down position (i.e., a "premature red" on the track clearance phase).

Roadway Standards: The MUTCD

The MUTCD (*1*) specifies that traffic signals at intersections within 60 m (200 ft) of a highway-rail grade crossing should be interconnected with the railroad warning equipment. However, if a method presented by Marshall and Berg (*7*) is used to calculate the warning time required to clear a 60 m (200 ft) queue, the warning time is found to be 25.6 seconds. This indicates that a conflict exists between the spacing guidelines and minimum warning times presented in the MUTCD, since crossings that are within both guidelines could still result in insufficient warning times. A signalized intersection queuing study by Oppenlander and Oppenlander (*8*) confirms that vehicle queues with an equivalent length of over 60 m (200 ft) can easily be formed at signalized intersections with moderate volumes, and reasonable splits and cycle length. Higher volumes, the presence of heavy vehicles, and longer cycle lengths further add to queue length.

To facilitate the traffic signal controller's ability to advance as quickly as possible to the track clearance phase, the MUTCD allows the abbreviation of minimum green time on non-track clearance phases, and it allows the abbreviation of pedestrian WALK and flashing DON'T WALK (i.e., pedestrian clearance) intervals. Unfortunately, the abbreviation of pedestrian clearance intervals can result in pedestrians being "stranded" in the middle of the intersection and in the path of the vehicles that are being released at the onset of the track clearance phase. This pedestrian-vehicle conflict is allowed in the MUTCD as a "relative hazard" to reduce the possibility of a vehicle-train conflict at the highway-rail grade crossing.

Railroad Standards: The *Signal Manual*

Like the MUTCD, the AREMA/AAR *Signal Manual* also specifies that the minimum warning time (MWT) provided at an actively controlled grade crossing should not be less than 20 seconds (*2*). However, the MWT can also be supplemented by multiple track clearance time, equipment/gate response time, and safety buffer time. The total warning time is then labeled the TWT. Finally, preemption time (PT) can be added beyond the TWT, if required by the highway agency, to allow the signalized intersection to go into preemption even earlier. Once the TWT and PT are added, the sum is the total approach time (TAT). However, the *Signal Manual* only leaves open the possibility of incorporating the PT into the TAT; there are no criteria or guidelines for its application. Thus, while the AAR guidelines offer some improvements over those specified by the MUTCD, they still do not address in any level of detail the additional time that may be needed by an interconnected signal. This additional time requirement often results from long signal clearance intervals or multiple clearance phase requirements.

Train Detection Practices

Several types of train detection systems are in use today. Conventional systems and basic motion detection systems use detection circuits that activate the warning devices as soon as a train enters the circuit. With such systems, the devices will be active longer before the arrival of a slower train, since that train will occupy the track circuit longer. A fast train, on the other hand, will occupy travel through the detection circuit at a faster rate and thus arrive in a shorter time after the warning devices have activated. Thus, the length of the detection circuit is such that the minimum (or set) warning time is provided for the case when the fastest expected train nears the crossing. All other trains will provide warning times that are longer than this set warning time. The lack of consistency in warning times that results from the conventional and basic motion detection systems has been shown to contribute to some undesirable driver behavior (*9,10*).

Constant warning time (CWT) motion-detection systems wait to activate the warning devices based on the train's predicted arrival time at the crossing. As their name implies, CWT systems are designed to provide more consistent warning times regardless of train speed on the crossing approach. The results from a study by Richards (*11*) indicate that constant warning devices could be used at crossings to increase safety. However, one problem with so-called "constant" warning time devices is that they are not constant and have the potential to produce warning times that are actually less than their design time. CWT systems are designed to establish a predicted arrival at the crossing within the first 15 percent of the approach circuit. The detection equipment will base the predicted arrival time at the crossing on the train's speed as it entered the circuit, even though the train may accelerate after entering a detection circuit. The accelerating train would arrive at the crossing before it was predicted to arrive and, hence, the warning time provided would be less than that which was set (*4*). Also, there remains variability in the warning time provided due to train acceleration and deceleration within the track circuit. The impacts of this variability must be considered when designing the signal settings for the preemption event.

IDEA PRODUCT: TPS LOGIC

The TPS is a logic algorithm whose objective is to improve the means by which traffic signal controller units prepare for a railroad preemption event. While maintaining the control requirements and standards explained in the MUTCD (*1*), TPS attempts to "ready" the signal control for the onset of an impending railroad preemption input, or call, by adjusting phase interval durations and phasing sequence order to avoid certain shortcomings of existing means of transitioning into preemption. These shortcomings include the abbreviation of vehicular phase minimum green times and the abbreviation of pedestrian WALK and/or flashing DON'T WALK (i.e., pedestrian clearance) intervals. TPS operates within the context of existing controller logic structure and manipulates controller operation by using standard interface "pins" or commands, depending on how the logic is connected (i.e., physically, as to a controller's backpanel, or logically, as to a digital interface or shared memory).

Prior to development of the TPS logic, the research team created a set of guiding principles for the design and operation of the system. These principles were essential to guarantee the usefulness of the TPS and to ensure the its appropriate, effective, and safe operation. The design principles include:

- The TPS must not interfere with or preclude the (normal) use of simultaneous or advance preemption at the intersection adjacent to the highway-rail grade crossing.
- The TPS will rely on second generation (i.e. non-intrusive) train detection technology, and must not affect or interfere with the current form of track circuitry in use by the railroad.
- The TPS will affect normal controller operation in an attempt to manage intersection vehicular phases, with consideration of driver expectation, to safely clear vehicles from the tracks (with a provision of buffer time) before a train's arrival at the highway-rail grade crossing, or prepare to do so, before the onset of simultaneous or advance signal preemption.
- The TPS will affect normal controller operation in an attempt to avoid, if at all possible, the shortening or omission of pedestrian WALK and clearance (i.e., flashing DON'T WALK) signal indications at the onset of simultaneous or advance signal preemption.
- The TPS will cease to have any impact on controller operations at the onset of simultaneous or advance preemption.
- The TPS will not cause the intersection signal controller to violate any of the provisions of the MUTCD (*1*) or the *Signal Manual* (*2*).

The TPS logic developed based on these principles is shown in Figure 1.

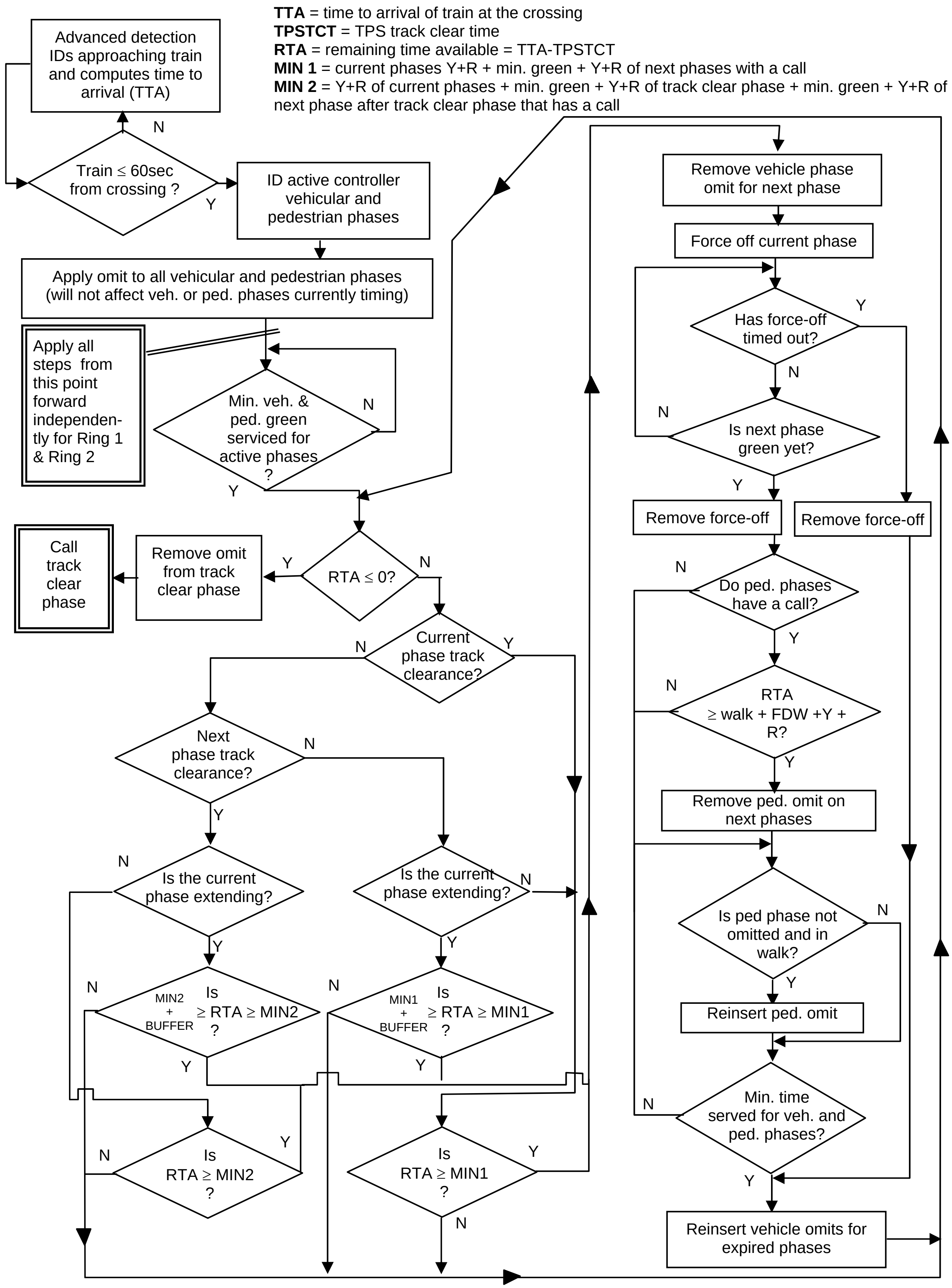

FIGURE 1 TPS logic algorithm.

The potential for TPS to provide benefits at signalized intersections with nearby highway-rail grade crossings can only be realized if responsible agencies believe that the phase abbreviations allowed by current standards must be minimized or eliminated altogether. Commitment would be required in developing new specifications for signal control equipment whose logic incorporated the TPS, or devices that can be reprogrammed or enhanced to include the TPS logic. In building devices that comply with the specification, manufacturer's would use this research as a starting point and then create logic code to ensure the compatibility of the TPS with their controller's internal phasing logic. This commitment would also include the installation of train detection devices (i.e., off-railroad through independent contract, or on-railroad with the cooperation of the railroad) that could sense approaching trains earlier in time than existing track circuitry.

The TPS, as developed in this research, is not ready for implementation. The variability of railroad warning times and the complexity of multiple standards and specifications in the traffic signal controller industry make generic traffic control solutions, such as the TPS, impossible in real-world environments unless the agencies, railroads, and manufacturers involved realize and agree on the need for improvements in current practice. A starting point for all of these affected parties is the examination of a new standard protocol for communicating train approach information to traffic signal controller units. Currently, this communication is restricted to a single, discrete electronic signal. While easy to troubleshoot and maintain, such limited information exchange means that, as a matter of necessity, current preemption practice is extremely limited. Should the public agencies and railroads ultimately agree on increased information exchange (as would seem probable in the future as more electronic monitoring is used), train estimated arrival times and information as to their reliability and variability may be provided. In such an information-rich environment, real-time control logic and processes, including the TPS, can be considered more realistic.

CONCEPT AND INNOVATION

Development and testing are currently underway in the area of train detection (*12*) using various types of technologies that may eventually be used and/or adapted to provide estimated train arrival, or estimated time of arrival (ETA) information to controllers at signalized intersections adjacent to highway-rail grade crossings. In its application to the TPS, ETA information would provide train arrival to the signalized intersection controller prior to either the normal train warning time provided by the railroad track circuits or any additional advanced warning time that may be provided for advance preemption at the signalized intersection. Doppler radar train detection has been used in past TTI research (*13*), and it will be used in field-based testing of the TPS logic.

The technologies listed below are provided as examples of possible detection technologies that have the potential to provide ETA information to systems such as the proposed TPS. The list is by no means exhaustive, as these technologies are merely presented as examples:

- GPS
- Automatic Equipment Identification/Radio Frequency
- Inductive loop
- Sonic
- Extension of Conventional Railroad Track Circuits
- Infrared
- Video
- Radar

To facilitate incorporation of the traffic signal control logic represented in the TPS into mainstream practices, specifications and/or devices, it was incumbent upon the research team to use phase referencing terminology found in the standards of the traffic signal control industry. Accordingly, the terminology used in formulating and presenting the TPS logic are based on phase referencing established by NEMA (*14*), and traffic signal controller unit inputs, outputs and functions are referenced as found in the NEMA TS-1 (*14*) and TS-2 (*15*) standards. Not only does the use of the appropriate standards terminology facilitate eventual incorporation of the research into practice, it also allows for ease of communication among research participants and ease of simulation and field testing of the TPS with authentic traffic signal control equipment.

Several versions of the TPS logic were created during the development stage. The most flexible and comprehensive strategy was selected for development and testing. The logic is shown in Figure 1 and is fully contained in Appendix A. The following variables are needed in order to understand and use the TPS logic:

- *Minimum vehicle time (MIN V):* Defined for each phase as the minimum time needed to service vehicles on a particular phase. This time is the sum of the minimum green time for a phase, the required yellow change interval time, and the required red clearance interval time.
- *Minimum pedestrian time (MIN P):* Defined for each phase as the minimum time needed to service pedestrians on a particular phase. This time is the sum of the WALK and flashing DON'T WALK (i.e., clearance) times for the phase.
- *Buffer time (BUFFER):* Defined for the intersection as the maximum extension to allow for a vehicle phase that has a call before forcing off that phase.
- *Time to Train Arrival (TTA):* This is the time the train is predicted to arrive at the crossing based on the train detection equipment.
- *TPS Track Clearance Time (TPS TCT):* The time before the train arrives at the crossing that the track clearance phase should be initiated.
- *MIN 1:* The minimum time necessary to service the next phase. (Simply the MIN V of the next phase)
- *MIN 2:* The minimum time necessary to service the next two phases. This is the sum of the MIN V from each of the next two phases in sequence.

Once the train detection equipment has indicated that train will arrive at the crossing within the TPS initiation time (assumed to be 70 seconds), the TPS logic would begin to monitor and, if necessary, affect controller operation. The following steps define TPS logic:

1. The status of the current phase(s) is (are) checked to determine if both the minimum green time and minimum pedestrian time have been serviced. If the minimums have not been completely serviced, the current phase(s) remains active. Otherwise, proceed to step 2.
2. If the Time to Train Arrival (TTA) at the crossing is less than the TPS Track Clear Time (TPS TCT), the track clearance phases are initiated. The TPS TCT is the preset desired time that the track clearance phase should begin prior to the train's arrival at the crossing. This time is determined by vehicle and geometric characteristics at the crossing and is usually longer than the warning time provided by the railroad equipment. Theoretically, the intersection would then be in track clearance every time the preempt call is received from the railroad equipment. This will lead to a more controlled and predictable entry into preemption.

If the next phase is the track clearance phase, the following steps are taken:

3. If there are still vehicle calls (detections) on the current phase, the phase is held green. Skip to step 5.
4. If there is enough time to service the minimum vehicle green time for the next two phases before the TPS Track Clear Time (i.e. TPS TCT $\geq$ MIN2), then the current phase will end and the next phase will begin timing. The pedestrian walk signal will only be displayed for the next phase if there is a pedestrian call on the phase and there is adequate time to completely serve and clear the pedestrians before the TPS TCT. If time is not available to display the next two phases for the minimum green time, the current phase will remain active. Skip to step 5.
5. At this point, the logic returns to Step 1 to ensure that the minimum times for the current phase have been satisfied.

If the next phase is *not* the track clearance phase, then the following steps are taken:

3. If there are still vehicle calls (detections) on the current phase, and the buffer time beyond the MIN V for the phase has not been reached, the phase is allowed to remain green (Skip to step 5). Otherwise, go to step 4.
4. If there is enough time to service the minimum vehicle green time for the next phase before the TPS Track Clear Time (TPS TCT), then the current phase will end and the next phase will begin timing. The pedestrian walk signal will only be displayed for the next phase if there is a pedestrian call on the phase and there is adequate time to completely serve and clear the pedestrians before the TPS TCT. If time is not available to display the next phase for the minimum green time, the current phase will remain active.
5. At this point, the logic returns to Step 1 to ensure that the minimum times for the current phase have been satisfied.

The TPS logic occurs in time before the onset of (normal) simultaneous or advance preemption of the traffic signal controller unit. The existing interconnection/preempt circuit remains in operation and fully retains its fail-safe backup features.

INVESTIGATION

Quantifying TPS Performance

A variety of traditional performance indicators exist to describe the efficiency and safety of standard traffic signal intersection operations. These indicators, known as measures of effectiveness, include stopped delay, queue length, number of stops, number of conflicts, and number of signal violations. Similarly, measures can be applied to assess the safety of a highway-rail grade crossing. In this case, measures describe vehicular behavior and performance during train passage, and include delay at the crossing, queue length, and number of gate (or other warning device) violations. However, few measures exist to describe the overall performance of an interconnected railroad warning device/traffic signal system. Several measures that will be used to describe the efficiency of the TPS algorithm in comparison to (normal) simultaneous or advance preemption are listed below:

- Delay on non-track clearance approaches
- Intersection average delay
- Queue length on the track clearance approach
- Pedestrian clearance abbreviations
- Vehicular minimum green interval abbreviations

Simulation Testing

Simulation of the highway-rail grade crossing and adjacent signal environment enabled testing of the TPS without the extreme expense of using realistic rail and highway testing grounds. The simulation could be made functional in a relatively short period of time, and contained many of the same control device elements found in the field. Simulation avoided the very real risk of failure implicit in any program of field experimentation. Also, simulation was useful in generating and recording descriptive measures of system performance. Generating these same measures under field conditions would have proven prohibitive in terms of staff availability and cost, and would have been subject to data collection and recording error.

A unique simulation and testing environment was assembled to make the laboratory test of the TPS as realistic as possible. An actual traffic signal controller unit, programmed with a full complement of vehicular and pedestrian phase settings, was connected to a roadway and train network simulation program using a controller interface device (CID). The CID essentially takes phasing information from the controller and sends it to the simulation on the PC, and it completes the loop by sending detection information from the simulator to the controller. Figure 2 shows the system. Figure 3 shows the simulation software that was used on the PC. The TPS logic was introduced into the simulation as a separate but integrated program, which is shown in the foreground of Figure 3.

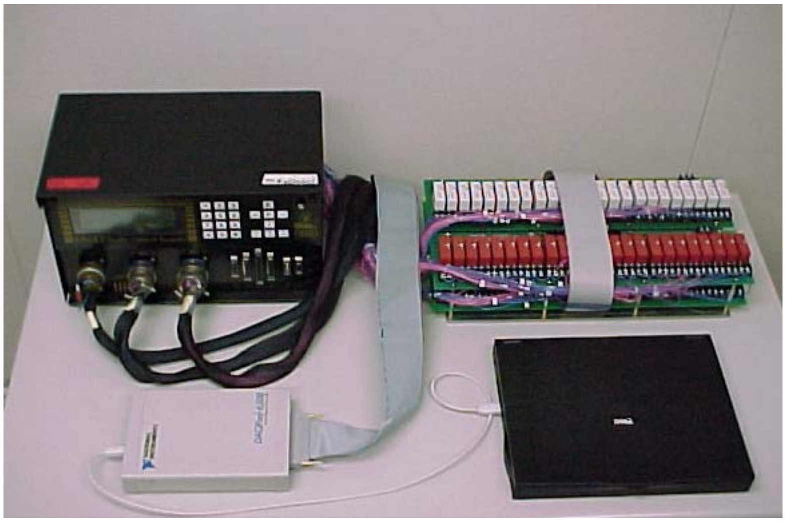

FIGURE 2 PC/Controller/CID simulation system.

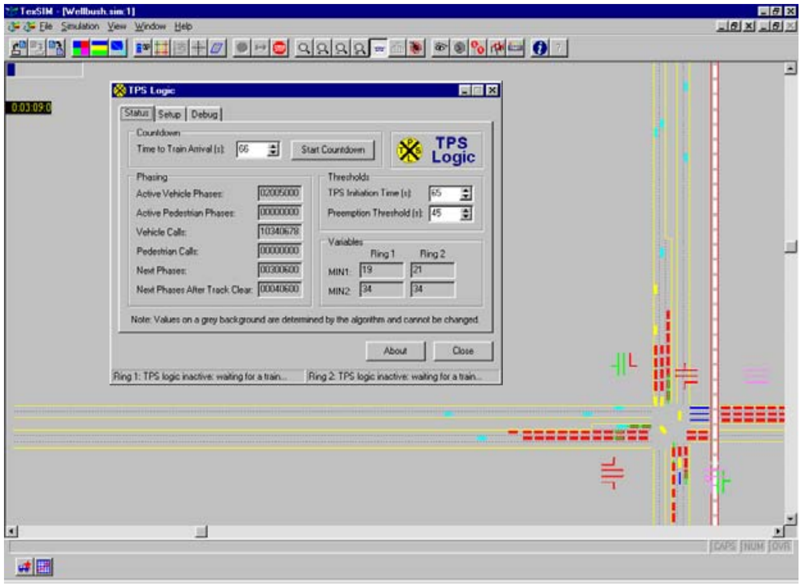

FIGURE 3 PC roadway and railway simulation software.

In addition to the information that the CID receives from the controller, information about phase times and order will also need to be known by the TPS logic, executing on the PC. This information is manually coded into the TPS logic program on the PC as an exact duplication of the settings in the traffic signal controller unit (see Appendix B). If the TPS logic were embedded in the controller, this duplication would not be necessary.

The CID/PC accomplishes the TPS routines outlined above by sending phase OMIT and ring FORCE OFF commands to the traffic signal controller unit. Once TPS is initiated, a phase OMIT is applied to all vehicle and pedestrian phases. This precaution prevents the controller from changing phases unless the TPS logic on the CID/PC instructs it to do so. The timing and order for the phases that is stored in the CID/PC is combined with the train detection inputs, vehicle detection inputs, pedestrian detection inputs and phase status inputs to determine which phase or phases should be called next. If the logic determines that there is adequate time to service the next phase, the OMIT is removed for that phase and the appropriate ring is sent a FORCE OFF command. This causes the desired phase to be displayed. Similarly, if a pedestrian phase needs to be displayed, the OMIT for that phase is removed.

Once the desired phase displays have been achieved, the OMITs are reinstated on all phases to prevent the controller from displaying an "undesirable" phase. It should be noted that if a true preempt call from the railroad equipment is received during anytime in this process, the controller will begin its normal programmed preemption routine regardless of the OMIT status imposed by the TPS logic. However, it is necessary to withdraw any TPS-imposed OMITs left after a preemption call is received (if any) so that the controller can operate properly during and after the preemption event.

During the software development and testing of the TPS logic, several problems were encountered with the TPS logic. The first problem related to the fundamental organization of traffic signal controller unit phasing logic. The basic format of this structure, known as a dual-ring, dual-barrier system, is shown in Figure 4. For the field site being used as a model for the TPS test case, the signal controller was not programmed to include phases 7 and 8. Essentially, there were no phases to the right of Barrier I in Ring 2.

TPS essentially assumes a management role over the normal functionality of the traffic signal controller unit (though not over the controller's special, preemption mode). In terms of narrative description, TPS "turns off" all of the vehicular phases and does not allow them to activate again unless there is sufficient time to serve them (i.e., at least their minimum and clearance times). For the TPS test file, this introduced a problem because of the dual-ring nature of traffic signal controllers and the special characteristics of the field site. Since the field site used its Ring 1 phases for all control over the cross street (i.e., this intersection is operating in a "split phased" mode, wherein the two opposing cross street approaches do not have simultaneous green), there were no cross street phases for Ring 2. As TPS assumed control over the intersection's traffic signal controller unit, there was no means for the logic to advance to the cross street phasing in Ring 2, since these phases did not exist.

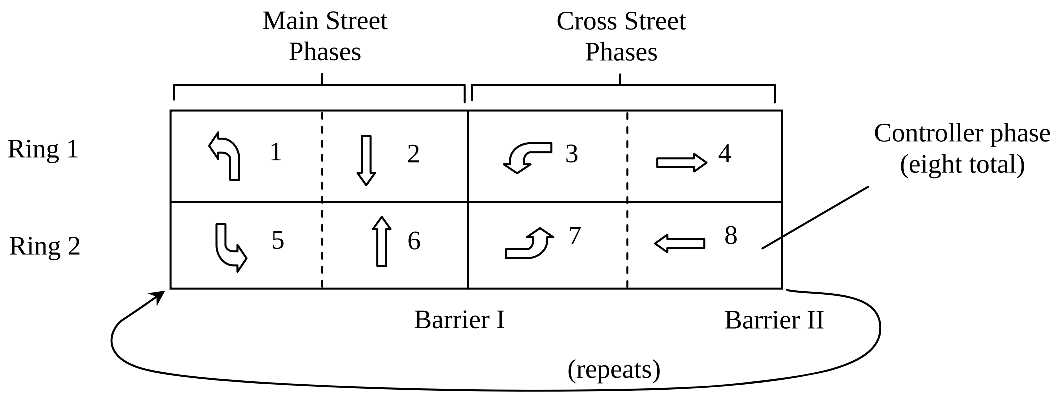

FIGURE 4 Basic dual-ring, dual-barrier controller logic.

An attempt to remedy this problem was implemented by dividing the TPS logic so that it acted on the controller's two logical rings independently. This improved the functionality of the TPS logic, and the controller still functioned safely and appropriately under TPS control. "Check out" features/timers were added into the TPS to cancel TPS controller management functions if those actions could not be enacted in a manner consistent with the logical and consistent operation of the controller.

Though these efforts did improve the TPS logic, they did not solve the dual-ring control problem introduced by the absence of phases to the left of Barrier I in Ring 2. However, this issue was left to be resolved by the incorporation of the TPS logic into traffic signal controller unit devices, as it was not a problem with the intent and operation of the TPS logic itself. The phase 7 and 8 omission problem was circumvented by artificially including these phases in the ring structures reported in the TPS database, even though these phases had no counterpart in the field.

Simulation Test Results

The simulation test impacts of the TPS on intersection operation are summarized in Table 1. Observation of Table 1 reveals that TPS caused a slight increase in intersection average delay and that it significantly reduced the number and duration of vehicular minimum green interval and pedestrian clearance interval abbreviations.

TABLE 1 TPS Simulation Test Results

MOE	Approach(es)	Train Frequency (trains/hour)	Without TPS	With TPS	Percent Change (%)
Average Stopped Delay (seconds/vehicle)	Non-Track Clearance	5	111.96	114.84	+2.6
		10	185.89	189.41	+1.9
	Track Clearance	5	18.13	16.98	-6.3
		10	20.55	19.72	-4.0
	Whole Intersection	5	93.49	95.05	+1.7
		10	151.57	153.58	+1.3
Average Vehicles in CSD at Preemption	Track Clearance	5	0	0	0.0
		10	3.67	1.89	-48.5
Number of Hourly Vehicle Minimum Green Abbreviations	Whole Intersection	5	2	0	-100
		10	1	0	-100
Hourly Seconds of Vehicular Minimum Green Abbreviations	Whole Intersection	5	22	0	-100
		10	14	0	-100
Number of Hourly Pedestrian Clearance Abbreviations	Whole Intersection	5	1	0	-100
		10	7	3	-57
Hourly Seconds of Pedestrian Clearance Abbreviations	Whole Intersection	5	15	0	-100
		10	39	19	-51

Several events occurred during the simulation and testing of the TPS logic which were unforeseen impacts of the TPS on traffic signal controller unit operation. The first relates to the means that the traffic signal controller unit uses to recover from a preemption event. Many controllers go into what is known as a "lockout" mode following preemption. During lockout, the controller places calls on all phases affected by the preemption event and serves them in their normal order. However, while the controller is in lockout mode, it does not "see" or receive external requests for phase OMIT or FORCEOFF functions. Thus, if one train has left the vicinity of the highway-rail crossing (and the signalized intersection is in lockout mode, attempting to recover from preemption) and another train is detected by the TPS's advanced warning system, the TPS system is rendered inactive because lockout prevents the TPS logic from exercising its management role over the traffic signal controller unit.

This limitation of the TPS does not limit or affect the normal preemption of the intersection, but it limits the activity and influence of the TPS where trains crossings are frequent. As this limitation on the TPS results from the means used to connect to the controller and/or its own programming during lockout mode, the resolution of this limitation is left to those (i.e., such as traffic signal software programmers) that may someday implement the TPS logic in their devices.

Another limitation on the TPS (as it was coded for the simulation test) is that it is possible to have a situation where normal signal preemption (either simultaneous or advance preemption) is initiated before the omit functions instituted by the TPS logic have expired. If this occurs, the controller may not be able to re-initiate the omitted phases during and after preemption, resulting in constant red signal indications for the affected phases. For obvious reasons, this is undesirable from an efficiency and safety perspective. Though it is improbable that this scenario will occur when the timing thresholds for the TPS are properly set, the fact that it is possible must be considered in the TPS logic design so that the TPS is as error-tolerant and robust as possible. It would appear possible to solve this problem by having the TPS logic monitor the normal railroad preemption circuit and remove all OMIT and FORCEOFF functions immediately after the normal preemption call is received. However, as soon as the signal controller unit goes into preemption, the OMITs may not be removable, depending on how the TPS logic interfaces with the controller unit. Further investigation will be necessary to find a means of solving this limitation in the context of the simulation's TPS logic.

Another remedy to the above-mentioned problem may be changing the means by which the TPS logic assumes a management role over the traffic signal controller unit. In the TPS logic tested using simulation, this management was made possible using phase OMIT and ring FORCEOFF functions. Alternatively, the HOLD phase functions could be used if the TPS logic we redesigned to HOLD phases until a desired termination time. In such a scenario, a previous phase would be "held on" until it was determined that sufficient time existed to service the next phase. However, this option was not explored, as it was unknown whether it would solve the limitation or introduce it in another form.

Field-Based Testing

Because of the favorable intersection impact results during the simulation test of the TPS, a field-based demonstration/test was pursued. The field study component of the research was made possible with the assistance of personnel and the use of hardware from TTI's TransLink® Research Center. TransLink's® Roadside Equipment Laboratory (REL) was instrumental in making the field-based test of the TPS system a reality. TPS made use of REL computers and hardware (specifically, a Doppler Radar train detection system) that were used to provide advanced train detection inputs to the TPS. Hardware was also available to perform traffic data collection and record the activities of traffic control devices at the study site.

Train detection was the first action conducted in each scenario where the TPS system was tested. In the field test, a detection threshold of 70 seconds prior to train arrival at the crossing was desired. The detector used to sense the approaching train and forward the detection information (i.e., speed, distance from detector) was a Doppler radar detection system used by TransLink® in the Wellborn Road intermodal test corridor in College Station, Texas. Several Doppler radar sensors were used for train detection and estimated time of train arrival (ETA) computation at the study crossing. An example of one of these sensors is shown in Figure 5. Several sensors were used in the corridor; the location of all sensors is shown in Figure 6. Whereas up to four sensors were used from those available in the test corridor, an advanced train detection system could operate reliably with only two directional sensors, one for each direction of train approach.

FIGURE 5 Doppler radar train detection system sensor.

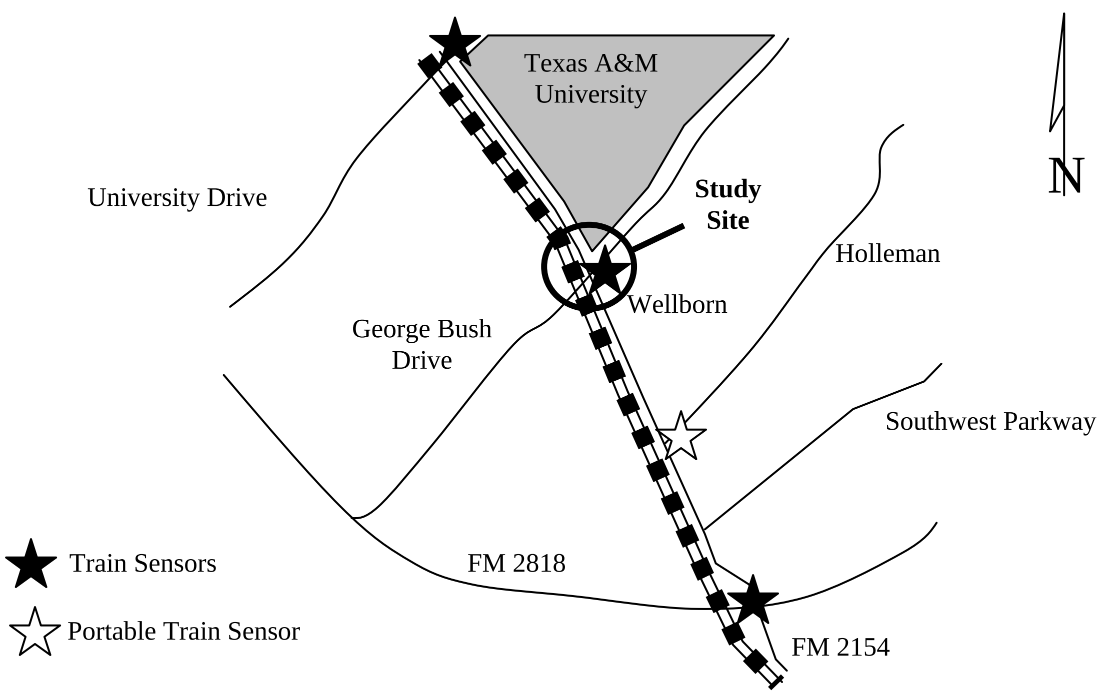

FIGURE 6 Location map for TPS field-based test site, College Station, Texas.

The equipment for computing crossing ETA information for the train, along with communications hardware for sending this information back to the TransLink® laboratory, was located in a TTI-installed traffic signal control cabinet at the intersection of George Bush Drive and Wellborn. Also located within this cabinet is the video camera control and signal communications equipment that allowed researchers to record live video of all approaches at the study intersection. A CID was installed in a controller cabinet used by the City of College Station, Texas to house the signal control equipment for the study intersection. This CID was used to record all vehicular, pedestrian, and railroad preempt signal status information during the data collection.

As it would be inherently impossible to perform a before-and-after test of the TPS on the exact same set of circumstances in the field, the before-and-after study was performed using the same hardware-in-the-loop simulation equipment used in performing the simulation test of the TPS. Using simulation, the exact same traffic and signal control circumstances used in the “before” case are repeated for the “after” case, except the TPS (along with the advanced rail detection input at the time its input was received in the field) is placed in an operating mode.

Fifteen-minute traffic volumes (see Appendix C) collected off of videos of intersection operations were converted to flow rates and entered in the simulation software. The length of the train detector and the length of the train itself were adjusted within the model for each preemption event to provide the warning time and crossing blockage time observed in the field. The advanced train sensing information recorded by the CID from the field Doppler radar train detection system indicated when the prediction algorithm estimated that the train was 70 seconds from the highway-rail grade crossing. The field-recorded time that the algorithm identified a train at this threshold (i.e., the initiation point of the TPS algorithm in the "after" study) was represented in the model by activating the TPS algorithm at the appropriate time.

Data were collected in the field between December 7, 1999 and December 13, 1999. Over the study period, 107 train preemption events were observed and recorded. Of these 107 events, 43 occurred between the hours of midnight and 6:00 AM, when video was not being recorded at the adjacent intersection (i.e., video was recorded in 6-hour blocks, from 6:00 AM to 12:00 noon, 12:00 noon to 6:00 PM, and 6:00 PM to 12:00 midnight). Of the remaining 64 preemption events, 10 had to be discarded because they took place in time too recently following a previous preemption event, and they (and their impacts on traffic at the adjacent intersection) could not be regarded as independent events. Three of the preemption events took place during morning hours (typically between 8:00 AM and 8:30 AM) when glare from the rising sun obscured the view of the adjacent intersection in the lens of one or both of the field video cameras. Of the original 107 preemption events during the study time frame, complete data were available for 51 preemption events, or trials, for the before-and-after study of the TPS logic.

Field-Based Test Results

Train detection in the field was composed of two parts; the normal, constant warning time circuit of the railroad and the Doppler Radar system used by TTI for advanced train detection. Both systems were found to have variability, which in turn affects performance. Figure 7 shows when the Doppler Radar train prediction system indicates that the train is 70 seconds from the crossing, and when the CWT device activates the signal controller's preemption circuit. Several things are apparent from examining Figure 7. First, while both Doppler and CWT exhibit variability, the Doppler system is more variable than the railroad's CWT circuitry. This was anticipated in that the CWT system is an off-the-shelf, tested, and frequently calibrated element of normal railroad signal control and monitoring hardware. The Doppler system, on the other hand, was installed for research and testing purposes and its train arrival prediction algorithm is a constantly evolving piece of software code. Also, the Doppler system in this field experiment detects trains at a more distant time threshold with respect to train arrival at the crossing (i.e., detection when the train is approximately 70 seconds from the crossing) than the CWT circuitry (i.e., minimum of approximately 35 seconds before train arrival at the crossing). As trains have a greater distance and time over which they may accelerate or decelerate, it was anticipated that Doppler warning times would be more variable than CWT warning times.

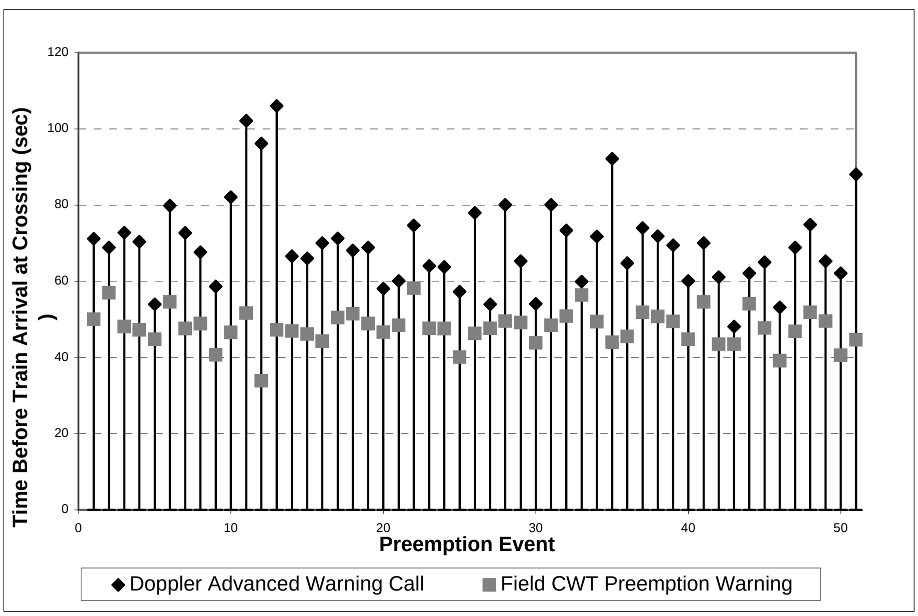

FIGURE 7 Train detection times for 51 preemption events.

The difference in time between the Doppler warning activation and the activation of the railroad's CWT circuitry (i.e., in the form of the crossing relay and electrified preempt pin into the traffic signal controller unit) is the advanced warning time provided to operate the TPS system. Figure 8 contains a histogram of the frequency distribution for the TPS advanced warning time. The TPS system was programmed considering Doppler detection 70 seconds before train arrival at the crossing, and normal preemption activation when the train was 48 seconds from the crossing. The 22-second average duration between these two times is when the TPS system can operate. These times were selected as a compromise between giving the TPS system more time to operate (i.e., more than 22 seconds would give the system more time to influence controller operation) and the increasing variability the farther in time the Doppler system gives its warning (i.e., Doppler warning time variability increases the farther the temporal detection horizon is set with respect to train arrival at the crossing). In reviewing Figure 8, note that TPS (i.e., Doppler) advanced warning times less than 17 seconds (when the system believes it has 22 seconds) could not logically provide the TPS system adequate time to make and act on control decisions for all possible traffic signal scenarios.

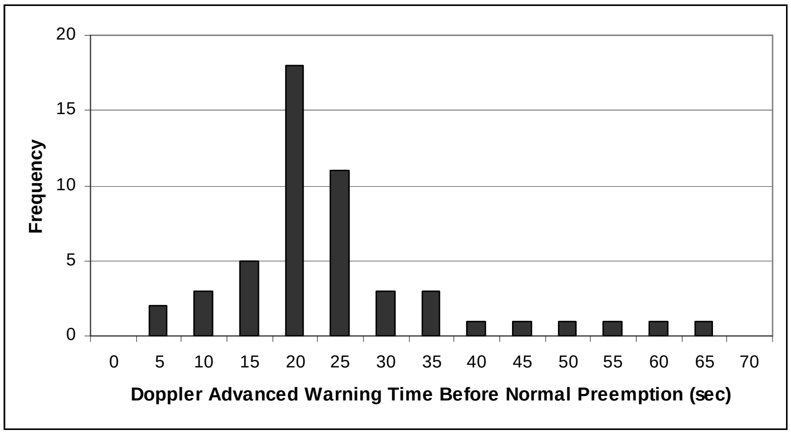

FIGURE 8 Advanced warning time available for TPS operation.

Where Doppler warning times were inadequate, traffic control at the intersection could not be influenced in a way that would result in operations that were "worse" than if the TPS system were not in operation in the first place. The normal railroad preemption circuit remains active; it is just that TPS benefits could not be realized with advanced Doppler warning times that were too short (i.e., less than 17 seconds). Where Doppler warning times were too long, on the order of more than 35 seconds (i.e., as would be the case where trains decelerated on their approach to the highway-rail grade crossing), the TPS system could operate effectively in terms of providing its benefits on the transition into preemption (i.e., vehicular minimum phase times and pedestrian clearance times were not abbreviated). However, in such cases the TPS system would hold in the track clearance phase until the normal CWT system went active and the signal controller was preempted. This led to long clearance phases and reduced intersection efficiency before train arrival at the CWT detection circuit.

Table 2 was created to provide statistical details for the warning time elements collected in the field and replicated in the simulation for the 51 preemption events. For each item, the absolute range, mean, and standard deviation are provided. Statistics are also provided for the duration of the 51 preemption events analyzed; these data are provided only because they were necessary for accurate simulation, not because they impacted the operation of the TPS.

TABLE 2 Warning Time Elements and Variability

Element	**Range (sec)**	**Mean (sec)**	**Standard Deviation (sec)**
Doppler Warning Time	48.1 – 106.1	69.81	11.94
CWT Warning Time	33.9 – 58.2	47.85	4.60
Advanced (TPS) Warning Time	3.6 – 62.3	21.95	12.33
Field Preemption Duration	59 - 307	167.75	60.22

As the only difference between the "before" and "after" simulations for each of the 51 preemption test events is the operation of the TPS system, sample independence cannot be assumed. Therefore, a paired t-test was used for statistical comparison of "before" and "after" data. Use of the paired t-test screens out the impact of the variability between data in each data set (i.e., caused by different volumes and signal setting across the 51 simulations). The paired t-test focuses attention on the differences between the before and after data for each of the total 51 simulation data sets.

Of the 51 simulation data sets, only 19 data sets had "reasonable" warning times. In this sense, "reasonable" indicates that Doppler warning times were both long enough to satisfy the minimum operational requirements of the TPS system (i.e., 30 warning times were too short) and not so long as to cause intersection inefficiency by an extended hold in the track clearance phase (i.e., 2 warning times were too long). In the following presentation of results, the data are first displayed in their entirety; then, only those data from simulations with reasonable Doppler warning times are shown. Paired t-test results on the delay differences for the before and after cases indicated no significant difference in the average intersection delay at the 95 percent confidence level. Details of the statistical comparison are shown in Table 3.

TABLE 3 Intersection Delay Statistical Comparison – Full Data Set

Element	TPS	Average Stopped Delay (sec/veh)	Standard Deviation	Paired t-value, $\alpha = 0.05$	Significant Difference ?
Track Clearance Approach	Off	19.99	4.20	-0.678	No
	On	19.74	4.16		
Non-Track Clearance Approach	Off	43.98	15.86	-0.017	No
	On	43.97	15.63		
Intersection	Off	38.84	12.44	-0.042	No
	On	38.81	12.15		

The subset of the 51 simulation data sets containing the 19 cases with adequate Doppler warning times show the same results for average delay as the full data set; no significant differences are found between the with and without TPS cases. Again, a paired t-test was performed on the delay differences, and a 95 percent confidence alpha-level was used. Delay values can be found in Table 4.

TABLE 4 Intersection Delay Statistical Comparison – 19 Adequate Warning Cases

Element	TPS	Average Stopped Delay (sec/veh)	Standard Deviation	Paired t-value, $\alpha = 0.05$	Significant Difference ?
Track Clearance Approach	Off	19.97	4.24	0.857	No
	On	19.56	3.52		
Non-Track Clearance Approach	Off	38.57	12.18	0.499	No
	On	38.02	10.96		
Intersection	Off	34.65	9.49	0.504	No
	On	34.20	8.72		

Queue length in the CSD between the intersection stop bar and the intersection-side limit of the highway-rail grade crossing has a relationship to safety. Logically, the fewer vehicles stored in the CSD at the time the railroad active warning gates block access to the highway-rail grade crossing, the lower the probability that a vehicle in queue is spilling back, or queued, into the crossing. The impact of the TPS system in signal operations with well-timed track clearance phasing and gate operations should be that, on average, the TPS starts the track clearance phase sooner and reduces its queue sooner than operations without TPS in place. These benefits can only be realized if the track clearance phase is of adequate duration and begins and ends at the appropriate time with respect to railroad crossing gate operation.

In the field study for this project, it was observed that, in some cases, the track clearance phase was terminating before the railroad crossing gate was fully descended. Unfortunately, this meant that there was an increased potential to allow vehicles into the CSD before train arrival and an increased potential than an uninformed motorist could be queued into the crossing (i.e., though it is illegal for motorists to queue (or stop) their vehicles within the crossing, not all motorists can accurately judge whether or not their vehicle can fit into an unoccupied gap within the CSD on the intersection-side of the crossing). The TPS system has the ability, given adequate advanced warning, to start the track clearance phase early (with respect to operations without TPS), essentially creating a "best" case or near best case situation where the intersection is already in the track clearance phase at the time normal, CWT railroad preemption begins. The track clearance phase then runs for its full duration, as programmed in the signal controller unit. TPS has no control (and has, in fact, ceased operation) over when the track clearance phase ends. If non-optimal track clearance phase/crossing gate arm coordination is present before TPS, it will remain even when TPS is active.

Non-optimal track clearance phase/gate arm coordination was present at the field site during the data collection effort. No effort was made to correct for this condition when the simulations of field-based data were made in order to preserve the integrity of the field data sets. The impact of the non-optimal phasing/gate arm coordination served to negate any benefits on track clearance phase queue reduction that might have been observed as a result of TPS operation (i.e., and its potential to start the track clearance phase sooner than non-TPS operation). For the reasons cited above, no significant difference was found between the before and after cases at the 95 percent confidence level using a paired t-test.

The TPS impact on signal controller operations most apparent to motorists would be the provision, in most cases, of minimum vehicular phase durations and pedestrian clearance times that are not abbreviated at the onset of normal preemption. As with the other MOEs used to gauge the impacts of TPS on intersection operation, the number of abbreviations and the quantity of minimum vehicular phase time or pedestrian clearance time were impacted by whether or not adequate Doppler advanced warning time was provided. Also, and in addition to Doppler advanced warning variability, the state of the controller at the onset of TPS operation was itself inherently variable (i.e., unpredictable from case to case). As TPS could not begin to influence controller operation until the active phase minimum had expired, the logic was effectively "frozen" for up to ten seconds in some cases, regardless of the amount of Doppler advanced warning provided.

The model outputs for the field-based simulation can be found in Appendix D. Paired t-tests of the before and after TPS data were conducted on both the number and total duration of vehicular minimum and pedestrian clearance phase abbreviations. Confidence results for the full data set and the 19 cases where adequate Doppler advanced warning were provided can be found in Table 5.

TABLE 5 Confidence Testing of Phase Abbreviation Results

<table>
<tr><th rowspan="2">Data Set/
MOE</th><th rowspan="2">TPS</th><th colspan="4">Number of Abbreviations</th><th colspan="4">Seconds of Abbreviation</th></tr>
<tr><th>Avg.</th><th>Std. Dev.</th><th>Paired t-value, $\alpha = 0.05$</th><th>Significant Difference ?</th><th>Avg.</th><th>Std. Dev.</th><th>Paired t-value, $\alpha = 0.05$</th><th>Significant Difference ?</th></tr>
<tr><td colspan="10">Full Data Set</td></tr>
<tr><td rowspan="2">Vehicular</td><td>Off</td><td>0.35</td><td>0.63</td><td rowspan="2">1.22</td><td rowspan="2">No</td><td>1.47</td><td>2.88</td><td rowspan="2">1.16</td><td rowspan="2">No</td></tr>
<tr><td>On</td><td>0.22</td><td>0.54</td><td>0.88</td><td>2.31</td></tr>
<tr><td rowspan="2">Pedestrian</td><td>Off</td><td>0.65</td><td>0.87</td><td rowspan="2">3.83</td><td rowspan="2">Yes</td><td>6.39</td><td>9.02</td><td rowspan="2">3.11</td><td rowspan="2">Yes</td></tr>
<tr><td>On</td><td>0.12</td><td>0.38</td><td>1.45</td><td>5.70</td></tr>
<tr><td colspan="10">19 Adequate Warning Cases</td></tr>
<tr><td rowspan="2">Vehicular</td><td>Off</td><td>0.53</td><td>0.70</td><td rowspan="2">3.29</td><td rowspan="2">Yes</td><td>1.84</td><td>2.99</td><td rowspan="2">2.69</td><td rowspan="2">Yes</td></tr>
<tr><td>On</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td rowspan="2">Pedestrian</td><td>Off</td><td>0.79</td><td>0.92</td><td rowspan="2">3.75</td><td rowspan="2">Yes</td><td>8.11</td><td>9.00</td><td rowspan="2">3.93</td><td rowspan="2">Yes</td></tr>
<tr><td>On</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
</table>

As shown in Table 5, the paired t-tests at the 95 percent confidence level indicate TPS effectiveness for reducing the number and total seconds pedestrian clearance time for the full data set. The paired t-test was not significant for the number and total seconds of vehicular minimum green abbreviation, despite the fact that the average number of abbreviations was reduced by 37 percent and the total seconds of abbreviation was reduced by 40 percent. The high variability of the data sets, especially in this case, had the affect of damping the difference in the sample averages.

For the 19 cases where adequate Doppler warning was provided prior to the onset of normal preemption, the differences in the number and seconds of both vehicular minimum green and pedestrian clearance abbreviation were significant at the 95 percent confidence level. Thus, in cases where sufficient advanced warning was provided, the TPS system could effectively reduce (in the observed data, it eliminated altogether) the minimum green and pedestrian clearance abbreviations found in normal preemption practice.

PLANS FOR IMPLEMENTATION

A Future for the TPS Logic

The TPS logic underwent a year-long development and testing effort during the research. As it was determined that advanced warning time variability creates unpredictability on the effectiveness of TPS operation, the TPS cannot be considered for current implementation. In the future, the TPS logic code can be used to derive an improved means for preparing intersection controllers for the onset of railroad preemption. For this to occur, additional detection is required for advanced train detection. An increase in information sharing between public highway agencies and railroads, especially as it pertains to providing more information about train approach to the signal controller of an intersection proximate to a grade crossing, would go far toward realizing the possibility of TPS implementation. Much of the logic for the TPS does not currently exist in many controllers. For this reason, new controllers (such as those that meet the 2070 specification) or new software for existing controllers would have to be purchased and installed at the intersection in order to eventually incorporate TPS-like logic directly into the controller.

Other issues arose during the TPS development and testing that should be noted, as they have an impact on the future usability of the TPS logic. Since the TPS uses OMIT and FORCEOFF functions to manage the intersection controller before normal preemption initiates, any other devices (i.e., such as bus priority devices/logic, emergency vehicle priority devices/logic, traffic signal coordination logic/devices, etc.) that make use of these functions will be impacted by TPS activity. Implementers of any TPS devices/logic must consider these impacts and mitigate or eliminate any influences or problems that arise from simultaneous operation. Also, the TPS simulation test was conducted on a controller that was programmed with very few additional functions, or features, that are in common use/practice, and which are designed to improve the operations and safety of the signalized intersection. The list below shows a few of these features.

- internal and external coordination/synchronization
- red rest
- simultaneous gap out
- call memory (locking, non-locking)
- dual entry
- last car passage
- conditional service
- vehicle and pedestrian phase recycling

No attempt was made to test how the TPS logic worked with these features, as the logic was developed and tested external to the controller device. The impacts of the TPS logic on all of these functions/parameters, as well as transition issues during controller operation (i.e., between phasing plans, into special operation modes, during and after preemption), must be fully explored and tested by TPS implementers. By considering each of these factors during TPS system integration, and by performing comprehensive testing of the system with the TPS logic in place, it will be possible to ensure that the logic is safely and appropriately implemented.

Enhancements to Existing Preemption Practice

The data collected in this project highlighted an important issue—*that the "constant" warning times produced by grade crossing prediction equipment are not really constant*. The warning time value used in the design of rail preemption is usually taken as the absolute minimum warning time that can be guaranteed by the railroad. However, in order to be able to guarantee this minimum value, the railroads provide, on average, a longer warning time to account for measurement errors and variation in train speed after activation of the signal preempt and the railroad warning devices.

Constant warning-type grade crossing predictor devices continuously update the travel time of the train to the crossing, based on the track circuit's measurement of current train speed and distance from the crossing. As soon as the predicted travel time is equal or less than the total warning time, the preemption notification is committed to the controller. However, there is a certain error in the measurement in the train speed and distance from the crossing, and that error is transferred to the predicted travel time. In addition, after the preemption notification is sent to the controller, the train may accelerate and decelerate before reaching the crossing, further increasing the warning time variation. A numerical analysis of data collected during this research indicated that slow, decelerating trains have the greatest effect on warning time variation. The variation in the measured warning time at the field site grade crossing is demonstrated by the cumulative warning time distribution graph shown in Figure 9. The graph was generated by fitting a log-normal probability distribution to the measured preemption warning times of the 107 events logged during the study data collection.

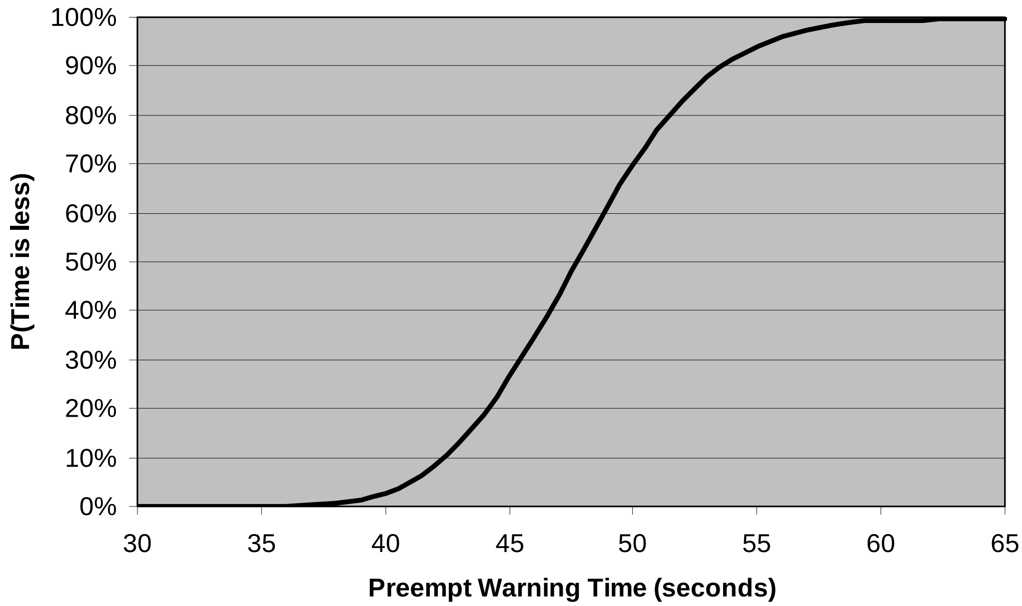

FIGURE 9 Cumulative probability distribution of preemption warning time.

The graph in Figure 9 indicates that there is a 95% probability that warning times can range between about 39 and 58 seconds, while the railroad guarantees a minimum preempt warning time of 35 seconds. The wide, 19-second variation in preempt warning time at the study crossing was mostly due to the relatively long 35 second minimum preempt warning time and the significant number of trains accelerating and decelerating when approaching the crossing (i.e., due to switching maneuvers north of the crossing).

In contrast with the preempt warning time, the variation in the railroad device warning time is much less, as shown in Figure 10. The graph was generated by fitting a log-normal probability distribution to the measured railroad device warning times of 25 trains at the study crossing; this data was collected independently from the data collection portion of this current study.

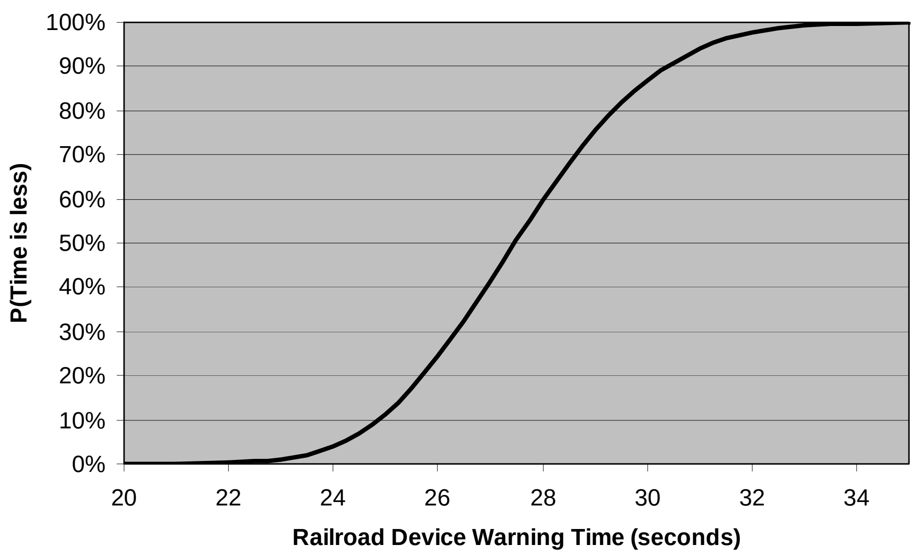

FIGURE 10 Cumulative probability distribution of railroad device warning time.

Figure 10 indicates that, while the railroad guarantees a minimum warning time of 20 seconds, there is a 95% probability of warning times ranging between about 23 and 32 seconds. Note that this 9-second variation is significantly less than the 19 seconds of variation for the preempt warning time. This is expected, since the preemption signal is sent to the traffic signal controller at least 15 seconds earlier than the activation of the railroad warning devices, and is therefore, for the reasons mentioned above, more variable than the railroad warning device activation signal.

Based on the numbers above, and assuming perfect correlation between the preempt warning time and the railroad device warning time, the preempt notification may occur between 16 seconds (39 seconds – 23 seconds) and 26 seconds (58 seconds – 32 seconds) before the railroad warning device activation. In practice, however, the preempt warning time and the railroad device warning time are not perfectly correlated; therefore, one can expect an even larger variation in the advance preemption time (the difference between the preempt warning time and the railroad device active warning time).

For simultaneous preemption the advance preemption time is zero; and, since the preempt and rail warning devices are activated simultaneously, the preempt warning time and the railroad device warning time are perfectly correlated. Therefore, it is relatively easy to coordinate the traffic signal preemption sequence with the rail warning device operation. In particular, it can be ensured that the gates are down before the track clearance green ends to ensure that no vehicles enter the crossing after the end of the track clearance phase.

For advance preemption, however, it is not as straightforward to coordinate the traffic signal preemption sequence with the rail warning device operation because of the uncertain duration of the advance preemption time. Under certain conditions, particularly when the advance preemption time is much longer than expected, it is possible that the track clearance phase terminates before the activation of the warning devices. In such a "premature red" scenario, vehicles may stop on the track after the end of the track clearance phase and consequently not get another opportunity to move off the track before the train arrives, in effect defeating the objective of the preemption sequence.

Therefore, the effect of the variation in warning time is twofold:

1. If the variation in warning time is not taken into account, the preemption scheme may fail in an unexpected mode, such as the "premature red" scenario described above.
2. If the effect of the variation in the preempt warning time is taken into account, the design of a preemption scheme becomes more complicated. However, advanced analytical tools such as fuzzy logic and the Monte-Carlo method exist, and can be used to adequately design for the stochastic nature of warning times.

Enhancing on the current binary (i.e., on-off) communication protocol may minimize variability between the railroad grade crossing predictor and the traffic signal controller and, to some degree, minimize the negative effects of variable warning time. Rather than just sending an on-off preempt signal to the traffic signal controller, the grade crossing predictor could send a continuously updated (with steadily improving accuracy) stream of expected train arrival times to the traffic signal controller. This would allow the controller to adapt its preemption sequence to variation in warning times. As an example affecting the current research, the TPS algorithm could be improved to take advantage of such a higher level of information by continuously updating its parameters and decisions based on the expected arrival time of the train at the crossing.

Another, less "high-tech" solution to the premature red problem would be to have the end of the track clearance green actuated by a signal generated when the gates are down, or alternatively, when the train reaches the island track circuit. However, existing controllers would have to be adapted to provide this functionally, and an additional interconnect circuit would be required between the grade crossing predictor and the traffic signal controller.

Research Needs

Examination and analysis of the data collected in this project identified a number of issues that have to be addressed through future research. These research needs relate to future enhancements of the TPS system developed in this project, current practices of detecting trains, means for providing information to traffic signal controller devices concerning train approach to/arrival at a nearby highway-rail grade crossing, and today's preemption practices.

1. Preemption schemes depending on a single warning signal from the grade crossing prediction equipment at a specified time before the train arrives at the crossing may not work well when the warning time is highly variable

(i.e., such as at the George Bush/Wellborn crossing used in this study). This need applies to the TPS logic as well. To rectify warning time variability problems and how they affect TPS operation, a continuously updating version of the TPS logic could be developed to determine if algorithm efficiency can be increased.

2. Existing preemption design procedures do not take into account the inherent variability in warning times. It is recommended that design procedures for preemption of existing traffic signal controllers be modified to take into account the variability in warning time. Advanced analytical tools such as fuzzy logic and the Monte-Carlo method may be necessary to accomplish this objective.

3. One method of addressing the “premature red” problem is to provide for the actuation of the end of the track clearance green by either a “gate down” signal or when the train reaches the island track circuit. It is important that researchers begin investigating ways to provide this capability through retrofitting current traffic signal controllers, and in the design of future traffic signal controllers. This “premature red” issue, where the track clearance phase terminates before gate arm descends, is especially problematic where highway-rail grade crossings are located very close (i.e., less than a few car lengths) to the signalized intersection.

4. Future research of railroad traffic signal preemption should be performed to fully explore and document the impacts of railroad preemption warning time variability. As indicated in the field investigation phases of this research, warning time variability has a direct impact on the coordination of traffic signal operation and active crossing warning devices. A thorough data collection and investigation would reveal additional information about the impacts of warning time variability on signalized intersection delay and queuing, the distribution of vehicular and pedestrian delay around the intersection, and the sensitivity of these measures of performance.

INVESTIGATOR PROFILES

Steven Venglar (Principal Investigator): Mr. Venglar has been involved with research activities at the Texas Transportation Institute (TTI) since 1992. His primary responsibilities have been focused in the areas of transportation operations modeling, analysis and evaluation. Through his work experience at TTI, he has become involved in all areas of transportation engineering, modeling, and traffic signalization. In addition to serving as the principal investigator on the current, TRB IDEA effort to traffic signal preparation for railroad preemption, he is heading up a GPS/GIS transportation network monitoring project for the City of Austin, Texas. In performance of engineering and analysis studies for south Texas districts of the Texas Department of Transportation (TxDOT), he has extensively used the CORSIM, PASSER II, PASSER III, Transyt-7F, and Highway Capacity Software analysis tools.

Mr. Venglar's applied engineering experience includes analysis and management of traffic engineering projects and contract studies for the TxDOT Research Division and the TxDOT Austin, Laredo, San Antonio, and Pharr Districts. He conducted a detailed study for origin-destination and operations modeling of the freeways and primary arterials in San Antonio using Integration and he participated in TTI's effort to assemble an Intelligent Transportation Systems Strategic Plan for TxDOT. He has taken responsibility as a project leader in efforts to develop a real-time control and optimization algorithm for signalized diamond interchanges, in an investigation of freeway incident management in Austin, Texas, and in a study to determine the impacts of light-rail transit in at-grade signalized environments.

Marc Jacobson: Marc Jacobson began his career with the TTI Research and Implementation Office in San Antonio. As an Assistant Research Scientist with TTI Mr. Jacobson’s research areas included frontage road access management, ITS before-and-after evaluations, traffic signal communications, and traffic signal preemption at railroad-highway grade crossings. In addition, Mr. Jacobson was a primary researcher on several projects for the San Antonio and Pharr Districts of TxDOT.

In 1999 Mr. Jacobson began working for the Public Works and Transportation Department of the City of Dallas as a Traffic Engineering Assistant. His responsibilities include traffic signal timing, signal warrant analyses, traffic signal design, and assisting with the development of an ITS plan for the City of Dallas. He is experienced with implementing traffic signal preemption routines in the field at railroad-highway grade crossings and the effects of preemption on traffic flow.

Roelof Engelbrecht: Roelof Johannes Engelbrecht was born and raised in Johannesburg, South Africa. After completing his undergraduate curriculum and after a year of compulsory military service, Mr. Engelbrecht joined the consulting engineering firm BKS Incorporated in 1991. He conducted numerous transportation modeling, public transport, traffic impact, parking and corridor studies of varying magnitude. He was involved in conducting a number of research projects sponsored by the South African Department of Transportation, and acted as Assistant Residential Engineer on a $4.5 million road and bridge construction project.

Mr. Engelbrecht left BKS at the beginning of 1995 to join the Department of Civil Engineering of the Rand Afrikaans University as lecturer. He left RAU at the end of 1995 to pursue a Masters degree in Transportation Engineering in the USA. In January 1996 he enrolled at Texas A&M University for a M.S. degree in Transportation Engineering. While working as a Graduate Research Assistant in the Design and Operations Program at TTI, he co-authored a research report to revise Chapter 9 and 11 of the Highway Capacity Manual. He also conducted traffic engineering studies for the Laredo District of TxDOT. As Graduate Research Assistant with the TransLink™ Research Center of TTI, he was a member of the PASSER™ III-98 software development team and the Smart Diamond research and development team. Mr. Engelbrecht is currently the principal investigator of a research project that integrates traffic signal controller hardware with traffic simulation models.

Srinivasa Sunkari: Between January 1992 and May 1995, Mr. Sunkari was involved in evaluating the Texas Traffic Light Synchronization Program and the Texas Traffic Management Program. He also developed the guidelines for implementing signal retiming projects for arterials, networks, and freeway corridors for TxDOT. He was in charge of the field implementation of the Smart Diamond Project in College Station, Texas. Taking a three-year respite from TTI, he worked for ITT Industries between May 1995 and October 1998. While at ITT, he was responsible for the field evaluation of the FHWA-sponsored RT-TRACS project in Reston, Virginia. He also participated in numerous fields activities for evaluating and calibrating the FHWA’s CORSIM simulation model.

After returning to TTI in 1998, Srinivasa Sunkari has been developing training workshops for implementing improved operations at signalized diamond interchanges and at railroad highway grade crossings. He is also involved in implementing and evaluating a TxDOT-sponsored truck priority project in Sullivan City, Texas.

Leonard Ruback: Mr. Ruback join TTI in 1995 as an Associate Research Scientist in the Rail Research Center / AAR Affiliated Laboratory. His research focus was on the engineering design and development of an intelligent grade crossing controller in conjunction with the Positive Train Separation Project in the Pacific Northwest. In 1998 Mr. Ruback joined the TransLink® Research Center and currently serves as the ITS Field Testbed Manager with interests in communications, embedded control and intelligent vehicles. TransLink® research focuses on the application of advanced technologies and operating strategies for the next-generation of transportation management centers. Current activities include the design and deployment of an ITS corridor in College Station, TX for purposes of multimodal transportation research, the development of a prototype train monitoring system for traffic management, and research in the area of information conduits to motor vehicles and mobile individuals. Mr. Ruback holds a Bachelor and a Master degree in Electrical Engineering from Texas A&M University.

Prior experience was in the defense electronics sector with Honeywell/Sperry Flight Systems as an electrical engineer assisting in the design, development, and test of the ANVIS Display Symbology System (ADSS). The ADSS was an innovative extremely light-weight, helmet-mounted avionics instrument display system for use with night vision goggles. Duties included the design and construction of a helicopter avionics simulator, identifying interface requirements and circuitry improvements for adapting existing hardware from other programs into ADSS, performing considerable system-wide troubleshooting, and establishing test procedures for the evaluation and qualification of the ADSS system.

Jack Webb: Mr. Webb was an Assistant Research Engineer with the Transportation Systems Division of TTI between August 1996 and May 1999. He has more than ten years of experience in state department of transportation administration. Mr. Webb=s expertise is in the area of highway-rail grade crossing safety issues. Mr. Webb was a member of the TransLink[7] Research Center as a liaison for highway/rail related projects. Mr. Webb was also involved in the Association of American Railroads affiliated Research Laboratory efforts in the TTI Rail Research Center. He currently works lives and works in Dallas, Texas for Carter & Burgess, Inc.

Mr. Webb=s previous experience includes the selection, design, and management of highway/rail related signal and roadway safety improvements, as well as the development of guidelines for the interconnection and preemption of traffic signals and highway/rail grade crossing signals in the States of Florida and Oklahoma. He has worked extensively in the areas of highway/rail grade crossing safety and rail corridor consolidation improvement projects, including expert testimony on behalf of the States of Florida and Oklahoma during administrative hearing proceedings. Other involvements include the development of highway/rail crossing four-quadrant gate installations, planning and development of grade crossing monitoring systems linked to railroad control centers, the evaluation of highway/rail grade crossing low-cost overpass alternatives, depositions and testimony on the behalf of the State of Oklahoma during tort liability proceedings, and certified presentations for public awareness of safety issues concerning highway/rail grade crossings.

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APPENDIX A – BORLAND DELPHI TPS LOGIC CODE

```
unit TPSLogic;

interface

uses
  Classes, Messages, Texsim, SysUtils, Math, Windows, Dialogs, Forms;

type
  TTPSLogic = class(TThread)
  private
    { Private declarations }
  protected
    procedure Execute; override;
  public
    RingNumber: Integer;
    StatusStr: string;
  end;

const
  MaxPhases = 8;
  MaxRings = 2;

type
  TPhaseSet = set of 1..MaxPhases;

const
  NumPhases: Integer = 8;
  NumRings: Integer = 2;

  LastCallTime: Double = 0.0;
  ControllerIndex: Integer = 1;
  ActiveVehPhases: TPhaseSet = [];
  WalkPedPhases: TPhaseSet = [];
  VehCalls: TPhaseSet = [];
  PedCalls: TPhaseSet = [];
  NextPhasesWithCalls: TPhaseSet = [];
  NextPhasesAfterTrackClearWithCalls: TPhaseSet = [];
  Next1PhaseMinTime: array [1..MaxRings] of Double = (0.0, 0.0);
  Next2PhasesMinTime: array [1..MaxRings] of Double = (0.0, 0.0);

var
  CountDownTTA: Boolean;
  PhaseStartTime,
  PedStartTime: array[1..8] of Double;
  TimeToTrainArrival,
  RemainingTimeAvailable: Double;
  MinVehTime: array [1..MaxPhases] of Double;
  MinPedTime: array [1..MaxPhases] of Double;
  VehChangeTime: array [1..MaxPhases] of Double;
  NextPhase: array[1..MaxPhases] of Byte;
  Ring: array [1..MaxRings] of TPhaseSet;
  ConcurrentPhases: array[1..MaxPhases] of TPhaseSet;
  TrackClearancePhases: TPhaseSet;
  TPSInitiationTime: Integer;
  TrackClearanceTime: Integer;
  BufferTime: Double;

implementation

{ TTPSLogic }

procedure TTPSLogic.Execute;
var
  i: Integer;
  NextPhasePedTime: Double;
  NextPhaseWithCall: Integer;
  NextPhasePedCalls: TPhaseSet;
```

```
  TimeOut: Boolean;
begin
  {run loop forever...}
  while True do
  begin
    {wait for train to come in range}
    StatusStr := 'TPS logic inactive: waiting for a train...';
    repeat
      Application.ProcessMessages;
      Sleep(50);
    until (TimeToTrainArrival > 0.0) and (TimeToTrainArrival <= TPSInitiationTime);

    { Start TPS logic. }

    {omit all vehicle and ped phases}
    for i := 1 to MaxPhases do
      if i in Ring[RingNumber] then
      begin
        {omit vehicle phases}
        SetControllerPhaseOmit(ControllerIndex, i, 1);
        {omit pedestrian phases}
        SetControllerPedOmit(ControllerIndex, i , 1);
      end;

    {wait for min phase and ped time to be serviced}
    StatusStr := 'Waiting for minimum phase time to expire...';
    repeat
      Application.ProcessMessages;
      Sleep(50);

    until GetControllerRingStatus(ControllerIndex, RingNumber) > 0;
    StatusStr := 'Dwelling in green...';

    {only run TPS while there is remaining time available}
    while RemainingTimeAvailable > 0.0 do
    begin
      {find next phase with call}
      NextPhaseWithCall := 0;
      for i := 1 to MaxPhases do
        if i in NextPhasesWithCalls*Ring[RingNumber] then
        begin
          NextPhaseWithCall := i;
          Break;
        end;

      {only run TPS logic if there are calls on other phases}
      if NextPhaseWithCall <> 0 then
      begin
        {check if the next phase can be serviced}
        if ((TrackClearancePhases*ActiveVehPhases*Ring[RingNumber] <> []) and
            (RemainingTimeAvailable >= Next1PhaseMinTime[RingNumber]))
          or
           ((TrackClearancePhases*ActiveVehPhases*Ring[RingNumber] = []) and
            (TrackClearancePhases*[NextPhaseWithCall] = []) and
            (GetControllerRingStatus(ControllerIndex, RingNumber) <> 1) and
            (RemainingTimeAvailable >= Next1PhaseMinTime[RingNumber]))
          or
           ((TrackClearancePhases*ActiveVehPhases*Ring[RingNumber] = []) and
            (TrackClearancePhases*[NextPhaseWithCall] = []) and
            (GetControllerRingStatus(ControllerIndex, RingNumber) = 1) and
            (Next1PhaseMinTime[RingNumber]+BufferTime >= RemainingTimeAvailable) and
            (RemainingTimeAvailable >= Next1PhaseMinTime[RingNumber]))
          or
           ((TrackClearancePhases*ActiveVehPhases*Ring[RingNumber] = []) and
            (TrackClearancePhases*[NextPhaseWithCall] <> []) and
            (GetControllerRingStatus(ControllerIndex, RingNumber) <> 1) and
            (RemainingTimeAvailable >= Next2PhasesMinTime[RingNumber]))
          or
           ((TrackClearancePhases*ActiveVehPhases*Ring[RingNumber] = []) and
            (TrackClearancePhases*[NextPhaseWithCall] <> []) and
            (GetControllerRingStatus(ControllerIndex, RingNumber) = 1) and
```

```
      (Next2PhasesMinTime[RingNumber]+BufferTime >= RemainingTimeAvailable) and
      (RemainingTimeAvailable >= Next2PhasesMinTime[RingNumber])) then
  begin
    {save next phase ped calls}
    NextPhasePedCalls := PedCalls;

    {remove vehicle phase omit on next phase with a call}
    SetControllerPhaseOmit(ControllerIndex, NextPhaseWithCall, 0);

    {force off current phase}
    SetControllerRingForceOff(ControllerIndex, RingNumber, 1);

    {wait for next phase to turn green, or for the available time to expire}
    StatusStr := 'Waiting for next phase green...';
    repeat
      Application.ProcessMessages;
      Sleep(100);
      {check if MIN1 or MIN2 is the threshold -- if the next phase with a}
      {call is track clearance, the we are dealing with MIN2}
      if TrackClearancePhases*[NextPhaseWithCall] <> [] then
        {MIN2 is the threshold}
        TimeOut := RemainingTimeAvailable < Next2PhasesMinTime[RingNumber]
      else
        {MIN1 is the threshold}
        TimeOut := RemainingTimeAvailable < Next1PhaseMinTime[RingNumber];
    until (GetControllerRingStatus(ControllerIndex, RingNumber) = 0) or TimeOut;

    {remove force off}
    SetControllerRingForceOff(ControllerIndex, RingNumber, 0);

    {phase will only be green if the wait for it to come on did not time out}
    if not TimeOut then
    begin
      {check if there is a ped call on the next phase}
      if NextPhasePedCalls*[NextPhaseWithCall] <> [] then
      begin
        {calculate time to serve next phase peds}
        NextPhasePedTime := MinPedTime[NextPhaseWithCall]+
          VehChangeTime[NextPhaseWithCall];

        {check if there is time to serve next phase peds}
        if RemainingTimeAvailable >= NextPhasePedTime then
        begin
          {remove ped omits on next phase with call}
          SetControllerPedOmit(ControllerIndex, NextPhaseWithCall, 0);
        end;
      end;

      {wait for minimum phase time to expire}
      StatusStr := 'Waiting for minimum phase time to expire...';
      repeat
        Application.ProcessMessages;
        Sleep(50);
        {Note: with a constant ped call the phase cycles between walk and}
        {ped clear, and thus never goes out of minimum phase time. To fix}
        {this, put the ped omit back after the walk comes on}
        if NextPhaseWithCall in WalkPedPhases then
          SetControllerPedOmit(ControllerIndex, NextPhaseWithCall, 1);
      until GetControllerRingStatus(ControllerIndex, RingNumber) > 0;
      StatusStr := 'Dwelling in green...';
    end;

    {reinsert all vehicle omits}
    for i := 1 to MaxPhases do
      if i in Ring[RingNumber] then
      begin
        {insert vehicle phase omits}
        SetControllerPhaseOmit(ControllerIndex, i, 1);
      end;
  end
end
```

```
      else
      begin
        StatusStr := 'No calls on any phases...';
      end;
      Application.ProcessMessages;
      Sleep(50);
    end;

    { End of TPS logic: go to track clearance phase, if there is one. }

    if TrackClearancePhases*Ring[RingNumber] <> [] then
    begin
      StatusStr := 'Calling track clearance phase...';
      {call track clearance phase}
      for i := 1 to MaxPhases do
        {only for ring under consideration}
        if i in TrackClearancePhases*Ring[RingNumber] then
        begin
          {first drop omit on track clearance phases}
          SetControllerPhaseOmit(ControllerIndex, i, 0);
          {then make sure track clearance phase is called by putting in a call}
          SetControllerVehDetectorActive(ControllerIndex, i, 1);
          {finally, force off ring}
          SetControllerRingForceOff(ControllerIndex, RingNumber, 1);
        end;

      {wait for track clearance phase green}
      StatusStr := 'Waiting for next phase green...';
      repeat
        Application.ProcessMessages;
        Sleep(50);
      until GetControllerRingStatus(ControllerIndex, RingNumber) = 0;
    end;

    {remove force-off}
    SetControllerRingForceOff(ControllerIndex, RingNumber, 0);

    {wait for train to reach the crossing}
    StatusStr := 'Waiting for train to reach the crossing...';
    repeat
      Application.ProcessMessages;
      Sleep(50);
    until TimeToTrainArrival <= 0.0;

    { Clean up after TPS logic. }

    {clear omits}
    for i := 1 to MaxPhases do
    begin
      if i in Ring[RingNumber] then
      begin
        {clear vehicle phase omits}
        SetControllerPhaseOmit(ControllerIndex, i, 0);
        {clear pedestrian phase omits}
        SetControllerPedOmit(ControllerIndex, i , 0);
      end;
      if i in TrackClearancePhases*Ring[RingNumber] then
        {clear track clearance phase calls}
        SetControllerVehDetectorActive(ControllerIndex, i, 0);
    end;

    Application.ProcessMessages;
    Sleep(50);
  end;
end;
end.
```

APPENDIX B – TPS LOGIC SETUP FILE

```
 [TPS-Logic]

MinVehTime[1] = 10
MinVehTime[2] = 10
MinVehTime[3] = 10
MinVehTime[4] = 10
MinVehTime[5] = 10
MinVehTime[6] = 10
MinVehTime[7] = 10
MinVehTime[8] = 10

MinPedTime[1] = 15
MinPedTime[2] = 15
MinPedTime[3] = 15
MinPedTime[4] = 15
MinPedTime[5] = 15
MinPedTime[6] = 15
MinPedTime[7] = 15
MinPedTime[8] = 15

VehChangeTime[1] = 5
VehChangeTime[2] = 5
VehChangeTime[3] = 5
VehChangeTime[4] = 5
VehChangeTime[5] = 5
VehChangeTime[6] = 5
VehChangeTime[7] = 5
VehChangeTime[8] = 5

TrackClearancePhases[1] = 3
TrackClearancePhases[2] = 8

TPSInitiationTime = 60
TrackClearanceTime = 30
BufferTime = 4.0
DefaultTimeToTrainArrival = 70.0
```

APPENDIX C – TRAFFIC COUNTS USED FOR FIELD-BASED STUDY

PE	Fifteen Minute Traffic Counts												Hourly Volume
	Northbound			Eastbound			Southbound			Westbound			
	Right	Thru	Left	Left	Thru	Right	Right	Thru	Left	Right	Thru	Left	
1	31	152	54	27	118	48	33	137	62	54	125	41	3528
2	12	95	29	25	103	41	38	138	67	36	101	39	2896
3	27	171	50	22	140	41	33	192	69	43	118	53	3836
5	28	123	29	19	109	36	26	126	63	67	96	50	3088
6	23	132	65	22	93	27	39	114	49	106	154	30	3416
7	26	69	27	18	76	41	19	81	36	41	83	24	2164
9	7	51	19	9	28	7	15	33	20	27	50	7	1092
15	28	140	20	20	40	11	6	50	15	53	58	8	1796
16	36	96	24	33	57	14	14	72	32	39	76	19	2048
18	35	161	45	32	96	47	22	122	67	82	118	37	3456
19	44	137	46	23	74	32	23	112	69	71	125	29	3140
22	27	115	38	17	103	33	26	136	74	72	109	40	3160
23	31	142	40	26	116	40	20	168	70	58	111	51	3492
24	28	87	39	18	78	40	17	125	60	57	121	37	2828
25	19	80	20	22	74	44	18	76	37	46	81	31	2192
26	19	76	30	10	60	29	30	96	47	51	63	29	2160
27	14	63	17	19	52	14	15	67	26	36	72	19	1656
35	51	158	42	27	107	24	20	108	71	67	97	28	3200
36	30	114	30	21	75	37	26	107	62	57	104	31	2776
37	28	128	34	21	120	38	33	148	77	48	107	55	3348
38	37	121	33	28	116	47	30	200	78	45	104	39	3512
39	26	71	26	11	46	19	18	88	29	40	67	13	1816
46	5	28	11	4	13	5	1	12	4	8	8	2	404
47	36	106	62	31	36	3	3	30	13	55	76	5	1824
49	27	91	31	20	63	20	11	63	33	42	54	9	1856
50	40	117	39	18	97	33	21	83	55	50	101	26	2720
51	64	184	67	41	128	40	23	146	78	134	163	51	4476
52	40	148	57	25	120	43	43	147	80	91	102	48	3776
53	26	102	21	36	140	57	35	195	99	68	101	65	3780
55	31	135	40	37	108	29	29	122	53	93	77	36	3160
56	17	88	22	16	78	24	26	95	49	44	84	35	2312
58	13	67	4	15	36	13	20	58	30	23	35	14	1312
70	15	84	14	10	70	19	9	53	38	30	46	11	1596
71	30	102	25	18	69	19	18	76	45	51	80	22	2220
72	31	108	35	16	86	22	16	77	54	59	75	27	2424
75	38	121	30	30	132	42	18	90	45	86	70	18	2880
77	15	119	24	24	69	19	31	188	74	99	147	46	3420
78	24	87	25	10	72	21	11	89	38	32	61	16	1944
80	21	79	16	6	52	14	17	80	35	35	51	24	1720
91	30	74	15	5	57	16	12	45	27	30	32	9	1408
92	36	113	27	18	81	17	11	91	38	53	70	17	2288
93	29	104	13	16	82	10	12	69	45	51	74	19	2096
94	24	70	35	16	78	18	9	70	32	46	65	20	1932
95	35	65	25	17	72	24	15	89	33	42	82	22	2084
96	29	93	24	13	61	34	16	14	48	32	69	25	1832
97	15	92	31	10	59	32	28	94	51	56	62	22	2208
98	26	54	10	14	52	16	17	83	32	42	57	21	1696
99	13	36	9	10	32	13	11	64	17	16	32	19	1088
109	37	125	33	21	72	27	15	96	57	49	76	16	2496
110	34	89	20	19	122	51	28	121	87	52	68	25	2864
111	37	140	58	22	109	47	34	143	72	77	107	24	3480

APPENDIX D – TPS SIGNAL IMPACTS FROM FIELD-BASED STUDY

Cars in CSD	With TPS Ped. Phase Status	Veh. Phase Status	Advanced Warning *	Cars in CSD	Without TPS Ped. Phase Status	Veh. Phase Status	PE #	Start Time	Start Day
2	no peds	3 past min.	0:17	4	2&6 ped. clr, 5s left	2&6 past min.	1	13:55:19	12/7/99
3	no peds	4 min., 5s left	0:07	3	2&6 ped. clr, 13s left	2&6 past min.	2	14:44:59	12/7/99
3	no peds	3 past min.	0:22	1	2 ped. clr, 15s left	2 min., 6s left; 5 min., 3s left	3	17:55:13	12/7/99
3	no peds	4 past min.	0:20	5	no peds	2&6 past min.	5	19:06:28	12/7/99
2	no peds	1&5 min., 4s left	0:07	3	no peds	3 past min. (in yellow)	6	20:01:06	12/7/99
1	no peds	4 past min.	0:21	1	2&6 ped. clr, 8s left	2&6 past min.	7	21:04:49	12/7/99
1	no peds	3 past min.	0:22	1	no peds	3 min., 3s left	9	22:45:08	12/7/99
2	2 ped. clr, 6s left; 6 past	2&6 past min.	0:16	2	2 ped. clr, 15s left; 6 ped. clr, 3s left	2&6 past min.	15	8:49:11	12/8/99
2	no peds	1&5 min., 2s left	0:17	2	no peds	1&5 min., 4s left	16	10:35:49	12/8/99
5	no peds	4 past min.	0:33	4	no peds	3 past min.	18	13:06:22	12/8/99
4	no peds	3 past min.	0:46	3	2 ped. clr, 12s left	2 min., 3s left; 5 all red clr	19	13:54:56	12/8/99
1	no peds	3 past min.	1:02	0	2 walk, 1s left (no clearance given)	2 min., 3s left; 5 min., 4s left	22	16:26:01	12/8/99
4	no peds	3 past min.	0:56	4	6 ped. clr, 2s left	1 min., 4s left; 6 past min.	23	17:48:35	12/8/99
3	no peds	1&5 past min.	0:17	3	no peds	4 past min.	24	18:40:26	12/8/99
2	no peds	2&6 past min.	0:17	2	no peds	4 past min.	25	19:57:52	12/8/99
2	no peds	1 past min.	0:22	2	no peds	3 past min. (in all red)	26	20:45:06	12/8/99
2	no peds	2&6 past min.	0:16	2	no peds	3 past min. (in yellow)	27	22:27:24	12/8/99
1	no peds	3 past min.	0:13	1	no peds	3 past min.	35	12:59:31	12/9/99
4	no peds	4 past min.	0:17	5	no peds	3 past min.	36	14:23:51	12/9/99
4	no peds	4 min., 4s left	0:09	4	2 ped. clr, 13s left; 6 ped. clr, 15s left	2&6 past min.	37	17:04:31	12/9/99
5	6 ped clr, 11s left	2 past min., 6 min., 2s	0:08	5	no peds	3 past min.	38	17:44:28	12/9/99
3	no peds	3 past min.	0:12	2	2&6 ped. clr, 4s left	2&6 past min.	39	21:09:22	12/9/99
0	no peds	3 past min.	0:13	0	no peds	3 min., 3s left	46	6:29:40	12/10/99
0	no peds	4 past min.	0:11	2	no peds	2&6 all red clr	47	7:17:47	12/10/99
0	no peds	4 past min.	0:16	0	no peds	4 all red clr	49	10:34:02	12/10/99
5	no peds	1 past min.	0:29	4	no peds	1&5 past min. (in yellow)	50	11:30:15	12/10/99
2	no peds	4 min., 5s left	0:03	4	2 walk, 3s left (no clearance given)	2 min., 9s left; 5 past min.	51	12:14:46	12/10/99
3	no peds	4 past min.	0:27	2	2 ped. clr, 15s left	2 min., 6s left; 5 min., 3s left	52	14:59:22	12/10/99
5	2 ped. clr, 5s left	2&5 past min.	0:12	5	no peds	3 past min.	53	16:57:47	12/10/99
2	2 walk, 1s left (no clr given)	2 min., 7s left; 5 min.,	0:08	4	no peds	3 past min.	55	18:39:36	12/10/99
3	no peds	2&6 past min.	0:28	5	no peds	3 past min.	56	20:07:46	12/10/99
3	no peds	2&6 past min.	0:18	3	2&6 ped. clr, 9s left	2&6 past min.	58	23:45:29	12/10/99
2	no peds	2&6 past min.	none	2	no peds	3 past min.	70	10:57:34	12/11/99
2	no peds	2&6 past min.	0:21	2	2&6 ped. clr, 9s left	2&6 past min.	71	13:31:38	12/11/99
0	no peds	3 past min.	0:45	0	2&6 ped. clr, 11s left	2 past min., 6 min., 2s left	72	14:19:11	12/11/99
3	no peds	4 past min.	0:17	3	no peds	3 past min.	75	16:03:51	12/11/99
4	no peds	2&5 past min.	0:18	4	no peds	3 min., 2s left	77	17:23:27	12/11/99
1	no peds	1&5 past min.	0:18	1	2&6 ped. clr, 10s left	2 past min., 6 min., 1s left	78	18:24:43	12/11/99
4	no peds	4 past min.	0:17	4	2&6 ped. clr, 9s left	2&6 past min.	80	21:36:25	12/11/99
1	no peds	3 past min.	0:13	1	no peds	4 past min.	91	12:08:22	12/12/99
3	no peds	3 past min.	0:11	3	no peds	2&6 past min.	92	13:59:17	12/12/99
3	no peds	4 past min.	0:15	3	no peds	2&6 past min. (in all red)	93	14:34:24	12/12/99
1	no peds	3 past min.	0:02	1	2 ped. clr, 6s left; 6 walk, 3s left (no clr)	2 past min., 6 min., 9s left	94	15:16:48	12/12/99
1	no peds	4 min., 6s left	0:04	1	6 ped. clr, 4s left	2&6 past min.	95	16:18:57	12/12/99
1	no peds	1&5 past min.	0:14	1	no peds	2&6 past min.	96	18:13:40	12/12/99
0	no peds	2&6 past min.	0:12	0	no peds	4 past min.	97	20:08:03	12/12/99
1	no peds	2&6 past min.	0:19	1	no peds	4 min., 6s left	98	20:52:49	12/12/99
1	no peds	2&6 past min.	0:19	1	2&6 ped. clr, 9s left	2&6 past min.	99	23:02:33	12/12/99
4	2&6 walk, 3s left	2&6 past min.	0:12	4	no peds	2&6 past min. (in all red)	109	9:32:19	12/13/99
1	no peds	2&6 past min.	0:20	1	no peds	3 past min. (in all red)	110	11:34:10	12/13/99
1	no peds	3 past min.	0:41	1	no peds	2&6 past min.	111	12:59:09	12/13/99

* Note: Advanced warning less than 17 seconds created potential problem with TPS system.