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Evaluation of the School Street Four-Quadrant Gate/In-Cab Signaling Grade Crossing System

Office of Research
and Development
Washington, DC 20590



Safety of Highway Railroad Grade Crossings

DOT/FRA/ORD-07/09

**Final Report
March 2007**

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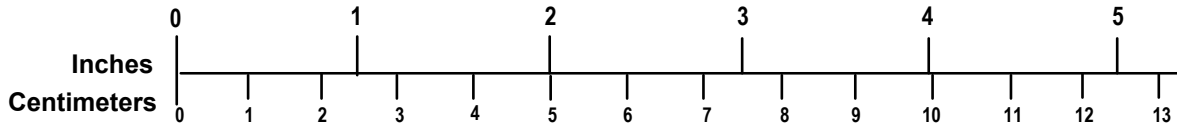
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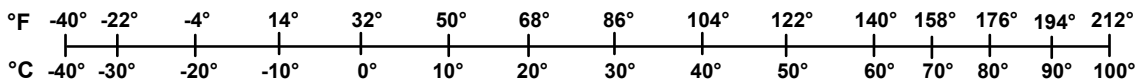
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Executive Summary

Under sponsorship from the U.S. Department of Transportation Federal Railroad Administration (FRA), Office of Research and Development, the John A. Volpe National Transportation Systems Center performed an evaluation of the four-quadrant gate/obstruction detection system at the School Street highway-rail grade crossing in Groton, CT. The primary objectives of this evaluation were to assess the safety benefits and to document the operational performance provided by this non-standard technology.

Highway-railroad grade crossing risk mitigation research in the United States has historically focused on the safety benefits of active warning devices, such as flashing lights, bells, and dual crossing gates. In addition, clear agreement has predominated within the research community that grade separation or closure provides the highest level of risk treatment. As the economic and societal costs of these treatments have increased, however, research has been increasingly concentrated on technologies that provide many of the same benefits without the obtrusiveness of grade separation or closure.

Two such technologies, four-quadrant gates and obstruction detection, were demonstrated at the School Street grade crossing along Amtrak's Northeast High-Speed Rail Corridor in Groton, CT. The purpose of this demonstration was to show that these technologies, when integrated with in-cab signaling, yield a high level of safety to motor vehicle users of the system without negatively impacting rail operations. Initial indications of the performance of this type of grade crossing safety enhancement system are that it will be a valuable treatment option for high-speed rail corridors throughout the United States where in-cab signaling or an equivalent type of train control system is used.

1. Introduction

High-speed rail travel can provide a means for transporting large numbers of people while increasing the safety of the overall transportation system. When a rail line is converted from conventional to high speed, various infrastructure improvements are required to maintain the level of safety. A case in point is the upgrade of Amtrak's Northeast Corridor (NEC) territory between New York City and Boston. In the 1960s, the need to create a high-speed rail system corridor between Washington, DC, and Boston was identified and investigated. The High-Speed Ground Transportation Act of 1965 responded to increased demand on rail service along the NEC by initiating a program of high-speed rail demonstrations. Over the last decade, legislation was enacted to coordinate efforts to increase the efficiency of Amtrak service on the NEC without impacting safety. In 1994, the *Northeast Corridor Transportation Plan* (NECTP) was published as a Report to Congress. NECTP was a comprehensive plan specifying the infrastructure and operational improvements necessary to implement a high-speed rail service between Boston and New York City. The infrastructure improvements included (1) electrification of the rail line between New Haven and Boston; (2) elimination of grade crossing hazards; (3) elimination of speed restrictions; (4) purchase of high-speed trainsets; and (5) installation of a high-speed signaling system.

The *Grade Crossing Elimination Plan* was included as an appendix to the NECTP. FRA, in coordination with the State Departments of Transportation (DOTs) and the respective local officials in Connecticut, Rhode Island, and Massachusetts, developed this document, mandated by the Amtrak Authorization and Development Act of 1992. The result of this work was a master plan for the closure, separation, or alternative treatment of the 15 remaining grade crossings on the NEC between New Haven and Boston (FRA, 1994). Under this plan, 12 Connecticut highway-rail crossings were slated for grade separation or closure. Several of the communities that would be affected by the proposed grade separation program, however, deemed that the grade separation or closure would be excessively intrusive (FRA, 1994).

As documented in the NECTP, FRA, Amtrak, and the Connecticut DOT (ConnDOT) conducted feasibility studies for the highway-rail crossing located at School Street in Groton. All three studies concluded that grade separation, at an estimated cost of \$4 million, was the only feasible solution. This conclusion was based on the density of rail traffic at the crossing and the fact that the crossing was the only entrance to the Willow Point neighborhood of Groton. Each of the recommendations, however, met with opposition from the local community over aesthetic and environmental concerns. The authors of the NECTP presented a potential alternative solution: the demonstration of an enhanced grade crossing system employing four-quadrant gates with obstruction detection, hereon referred to as the four-quadrant gate system. The key facets of this technology were the four-quadrant gates, detection of motor vehicles and other metal objects stalled on the highway-rail crossing, and the integration of the obstruction detection system (ODS) with the Amtrak nine-aspect cab signal system. The authors also acknowledged that the ODS component could increase the total crossing warning time from the minimum Connecticut State requirement of 30 seconds to as much as 150 seconds. The current law in the State of Connecticut mandates a minimum warning time of 30 seconds. This increase was necessary because of the time required for a locomotive engineer to execute safe braking in response to a reduction in the cab signaling system aspect (FRA, 1994).

1.1 Dual-Gate versus Four-Quadrant Gate Crossings

Dual-gate grade crossings reduce the risk level over passive crossings and crossings incorporating flashing lights. The gate warning time is one variable that affects the risk level of motor vehicle driver behavior. For a conventional grade crossing, track circuits installed at fixed distances in both directions from the crossing are used to activate the warning devices. This type of crossing is known as a fixed distance activation crossing. The relative positions of these track circuits with respect to the grade crossing are calculated to provide 20-30 seconds of warning time for the maximum civil speed at that location. For example, a crossing with a maximum civil speed of 70 mph (113 km/h) will provide a 30-second warning for a passenger train traveling at that velocity. However, the warning time for a freight train traveling at a speed of 35 mph (56 km/h) will be 1 minute. The lack of constant warning time devices at many crossings in the United States can pose a safety concern because motorists may not be accustomed to the variations. For dual-gate crossings that are not equipped with constant time warning devices, such as the pre-existing system at School Street, the concern is that motorists may become impatient and drive around the gates. The risk associated with this behavior is magnified for a rail corridor that experiences a mix of high-speed and conventional intercity, commuter, and freight rail service, such as the NEC in Connecticut.

One common grade crossing concern is the potential for motor vehicles to become disabled or stranded as a result of traffic congestion. The latter scenario often occurs when motorists realize the gates are descending and attempt to traverse a crossing before the gates are fully deployed. Each year, this scenario results in numerous collisions between trains and motor vehicles. Many of these collisions are potentially preventable by ODSs that are integrated with wayside and/or in-cab signaling systems.

Although four-quadrant gate crossings are not a substitute for grade separation in high-speed rail corridors, they are designed to mitigate the motor vehicle driver violations associated with dual-gate systems. By design, four-quadrant gate systems provide a visual blocking of a crossing and tend to prevent motor vehicles from driving around the deployed gates. These crossings may be envisioned as the conventional dual-gate system augmented by exit gates. The exit gates prevent automobiles from traversing the crossing against the direction of vehicle traffic flow. In the event of either a system failure or a vehicle becoming trapped within the crossing, the exit gates will raise to the up position, and the entrance gates will deploy to the down position. The addition of the ODS provides the two-fold capability of alerting approaching trains equipped with in-cab signaling devices to trapped vehicles and releasing the exit gates so that trapped vehicles are able escape the crossing.

1.2 High-Speed Rail and Grade Crossings

The study of grade crossing safety in high-speed rail corridors dates back to at least the early 1970s (FRA and Federal Highway Administration [FHWA], 1972). This research addresses what is now known as conventional high-speed rail service or speeds up to 110 mph (176 km/h). The first important research that examined grade crossing safety issues at speeds in excess of 110 mph (176 km/h) followed shortly thereafter (Hopkins, 1973). In his report, Hopkins characterizes the various grade crossing risk mitigation options and strategies for train speeds between 120 mph (192 km/h) and 150 mph (240 km/h). His recommendations include advanced

warning signals at crossings, pre-emption of nearby highway signals, four-quadrant gates, improvements to flashing lights at gates, constant warning time circuitry, and trapped vehicle detection systems. This appears to be the first report in the United States that promoted the usage of four-quadrant gates.

In the years since this work was first published, FRA has extensively researched grade crossing safety in the high-speed rail arena. Of this vast body of knowledge, FRA published *Rail-Highway Crossing Safety Action Plan Support Proposals* (Action Plan) in 1994. In the Action Plan, the authors identify the following six fundamental areas for furthering the cause of grade crossing risk mitigation:

- Increased enforcement of traffic laws at crossings
- Rail corridor crossing safety improvement reviews
- Increased public education and implementation of the Operation Lifesaver program
- Safety and private crossings
- Increased emphasis on data and research
- Increased trespasser prevention

The Action Plan also delineates three categories of high-speed rail: 80-110 mph (128-176 km/h), 110-125 mph (176-200 km/h), and speeds greater than 125 mph (200 km/h). In terms of high-speed rail lines, the Action Plan prescribes specific treatments for public and private grade crossings (listed in Table 1 by high-speed rail category).

On the NEC, the FRA Office of Safety has defined different rules for train speeds at grade crossings. For crossings with conventional warning systems, train speeds are not allowed to exceed 80 mph (128 km/h). However, the Office of Safety has also defined the requirements for high-speed crossings along the corridor. For crossings with four-quadrant gates and ODSs, train speeds as high as 95 mph (152 km/h) are permitted. In these instances, the ODS must be connected to the train in-cab signaling system such that a train will be brought to a stop should the crossing be determined to be occupied following descent of the gates.

The Office of Safety approved this deviation from the Action Plan because of the unique train control system installed on the NEC. The train control functionality is performed by two major components: (1) the nine-aspect cab signal system that maintains vital train separation and (2) the Advanced Civil Speed Enforcement System, an overlay speed enforcement system. The Office of Safety believes that these two components will provide sufficient risk mitigation such that high-speed train operations will be permitted at the specially equipped crossings.

Table 1. High-Speed Rail Grade Crossing Treatments

Rail Speed	Public Grade Crossing Treatment	Private Crossing Treatment
80-100 mph (128-176 km/h)	Eliminate all redundant or unnecessary crossings. Install most sophisticated traffic control/warning devices compatible with the location; e.g., median barriers, special signing (possible active advanced warning), four-quadrant gates. Automated devices should be equipped with constant warning time equipment.	Close, grade separate, and provide a secured barrier or automatic device for private crossings. Extend device or barrier across the entire highway on both sides of the track. Should normally be closed and opened on request, if no train is approaching, for a period of time sufficient to cross the track(s).
110-125 mph (176-200 km/h)	Protect rail movement with full width barriers capable of absorbing impact of a highway vehicle. Include a fail-safe vehicle detection capability between barriers. Notify approaching trains of warning device or barrier failure or of an intruding vehicle in sufficient time to stop short of the crossing without resorting to energy brake application.	Protect rail movement with full-width barrier or gate, normally closed and locked, capable of absorbing impact of a highway vehicle. Gate lock or control should be interlocked with train signal and control system and released by a railroad dispatcher. A fail-safe vehicle detection or video system should monitor the area between the barriers. The crossing should be equipped with a direct link telephone to the railroad dispatcher.
>125 mph (>200 km/h)	Close or grade separate all highway-rail crossings.	Close or grade separate all highway-rail crossings.

2. Literature Review

The earliest attempt to model grade crossing accident frequency and severity dates back to the 1972 FRA Report to Congress: *Railroad-Highway Safety Part II: Recommendations for Resolving the Problem*. The model further evolved under research performed by FHWA (Huntington et al., 1972; Coleman and Stewart, 1974; Coleman and Stewart, 1976) before reaching its final state under joint FRA and FHWA research (Mengert, 1980). Concurrent to the accident prediction modeling research was a separate effort to model the effectiveness of passive devices (i.e., crossbucks); active warning devices, such as flashing lights; and automatic gates in reducing grade crossing accidents (CPUC, 1974; Morrissey, 1980).

FRA culminated this research with the publication of the *Rail-Highway Crossing Resource Allocation Model* (DOT model) in 1981. After further research (Eck and Halkias, 1984; Farr and Hitz, 1985), the model was refined, and the revised version was published in 1986 (Farr, 1986). The two primary inputs to the model are the DOT accident prediction and accident severity formulas. The resource allocation model was developed to prioritize crossings by risk and severity to evaluate the societal benefits of grade crossing improvements, such as warning lights and automatic gates, within a selected group of crossings (i.e., all crossings within one state). By using a risk-based approach for estimating the effects of higher train speeds on grade crossing safety, Mironer et al. (2000) showed that the highest speed crossings in a corridor are not necessarily the highest risk crossings.

2.1 Previous Four-Quadrant Gate Studies

The first four-quadrant gate crossing in the United States began service in 1952 and has been operational ever since. However, the first major study of this technology was not conducted until 1989 in Knoxville, TN (Heathington et al., 1989). This research was performed using the before and after methodology of comparing the motor vehicle violation and collision rates of the pre-existing dual-gate crossing with the four-quadrant gate technology. The results of this evaluation showed that the four-quadrant gate had no impact on the level of service provided by the crossing and yielded an increase in safety as measured by the virtual elimination of risky behavior and motor vehicle violations (Heathington et al., 1989). Research resulted in the following major findings:

- The four-quadrant gate system eliminated gate violations.
- The number of vehicles traversing the crossing within 10 and 20 seconds of a train was eliminated.
- The four-quadrant gate system did not appear to increase the risk of a vehicle being trapped on the tracks with an exit gate delay of several seconds.
- Emergency vehicle operations through the crossing were not impacted.
- No unreasonable delays occurred for motorists at the crossing.

Four-quadrant gates are applicable for the following types of crossings:

- Four-lane undivided highways
- Crossings with multiple tracks separated by a distance greater than the length of a motor vehicle
- Crossings without constant time warning
- Crossings with traffic, such as hazardous material trucks, school buses, or high-speed passenger trains
- Crossings with high violation and accident rates

In the 1990s, the Volpe Center performed another before and after evaluation of four-quadrant gates in Charlotte, NC. In this study, two dual-gate crossings were upgraded with four-quadrant gates as part of Phase I of the North Carolina Sealed Corridor program. The results over a 5-year post-treatment period showed that risky motorist behavior, driver violations, and fatalities were eliminated, compared to 4 fatalities at the 2 crossings during a pre-treatment time span of 8 years (FRA, 2001).

The Los Angeles County Metropolitan Transportation Authority (LACMTA) performed another evaluation of a four-quadrant gate crossing with obstruction detection. This involved upgrading a dual-gate system to four-quadrant gates with obstruction detection on a crossing at 124th Street in South Central Los Angeles. The project was unique for several reasons: (1) it was the first four-quadrant gate installation at a U.S. light rail transit (LRT) crossing, and (2) the crossing operations consisted of LACMTA LRT and Union Pacific Railroad trains jointly operating on parallel tracks. This environment presented a confusing array of mixed mode traffic to motorists. The results of this study showed a significant decrease (~94 percent) in the number of motor vehicle violations during a 6-month period consisting of approximately 40,000 gate activations (LACMTA, 2000). LACMTA is in the process of duplicating this technology at approximately 10 other locations on its LRT system.

The Massachusetts Bay Transportation Authority (MBTA) evaluated a four-quadrant gate system with obstacle detection during a 9-month period in 1999. In this study, MBTA upgraded a dual-gate grade crossing to four-quadrant gates on its commuter railroad line in Abington, MA. Although this study was performed for demonstration purposes only, it was unique because magnetometers, a novel technology, were employed for obstruction detection. The results of this demonstration program were extremely favorable in proving that the technology works correctly. No experiment was performed to capture changes in motor vehicle violation rates (FTA, 2001).

2.2 Four-Quadrant Grade Crossing Modeling

The University of Illinois (Moon and Coleman, 1999) performed an excellent analysis of four-quadrant gate crossing operating parameters. The objectives of this research were to (1) optimize the timing parameters of the gates for a crossing without obstruction detection, (2) model the changes in optimal gate parameters with the introduction of four-quadrant gate technology, and (3) assess the safety and operational issues associated with a trapped vehicle detection system. The research resulted in the following major conclusions:

- The operating parameters of a four-quadrant gate crossing should be derived from the traffic, train, environmental, and driver behavior characteristics specific to that crossing.
- Motor vehicle violation rates did not significantly vary between dual-gate and four-quadrant gate models.

Coleman and Chitturi (2002) further refined the four-quadrant gate model to include the following:

- Pavement friction resulting from weather-influenced pavement conditions
- Motor vehicle driver decisionmaking under adverse weather conditions
- Weather-influenced pavement conditions that increase the risk of vehicle entrapment of near miss clearance incidents
- The rate of grade crossing collisions or near misses as a function of vehicle volume

The results of this work showed that concrete, asphalt, and snow-packed wet and dry pavement conditions did not increase risk. A significant increase in risk, however, was found for icy dry and icy wet pavement conditions. The revised model also indicated that an increase in the gate delay, or the time interval after initiation of flashing lights, significantly reduced or eliminated grade crossing collisions or near misses (Coleman and Chitturi, 2002).

2.3 Motor Vehicle Violations

Although some research of motor vehicle violations at grade crossings over the past 30 years has occurred, no one has developed a causal relationship between motor vehicle violations and collisions between trains and motor vehicles. The results of a study performed by Sanders (1976) showed that poor track surface conditions were the most common reason for motor vehicles to reduce speed at grade crossings. Shinar and Raz (1982) found that automatic dual-gates with flashing lights were associated with the lowest motor vehicle approach speeds when compared to crossbucks and flashing lights. The Heathington et al. (1989) study of a four-quadrant gate grade crossing in Knoxville, TN, showed no significant difference in motor vehicle brake rates at dual-gate and four-quadrant crossings. This result was surprising until the Heathington team found that the platooning of vehicles driving around the closed gates impacted motor vehicle brake rates at dual-gate crossings.

Meeker et al. (1997) performed a before and after study of driver behavior at a grade crossing initially equipped with flashing lights and then upgraded to dual gates. The results of this research showed that the addition of the gates decreased motor vehicle violations from 67 percent to 38 percent when the gates were closed. Another result of this study was that drivers who crossed around closed gates were significantly less likely to stop or slow on approach to the crossing than drivers approaching flashing lights only. Tenkink and Van Der Horst (1990) found that some motorists proceeded to drive through a crossing after a train had passed but before the warning lights were extinguished. This type of scenario could increase the probability of collisions with trains approaching from the opposite direction and signifies the need for second train coming signs. Richards and Heathington (1990) found that drivers were more likely to commit violations when measured crossing warning times were greater than 30-40 seconds. Abraham et al. (1998) found that motorists were more likely to commit hazardous violations at

multitrack, multilane road (grade crossings) equipped with dual-gates rather than passive crossings. The dual-gate crossings with the highest violation rates also had the highest accident rates, thereby justifying the need for four-quadrant gates.

Fitzpatrick et al. (1997) developed two logistic regression models to predict whether motor vehicle drivers will commit either flashing light violations or the riskier, typically enforced violations, from 2 seconds after gate initiation to time of train arrival. These models can be used to characterize hazardous grade crossings that may require further safety improvements. The inputs to these regression models are train speed, number of train tracks, warning time, sight distance adequacy, and the number of approach lanes. In a study of gate operating parameters by Moon and Coleman (1999), decreasing motor vehicle speeds were measured at approaches to dual-gate grade crossings under consideration for upgrades to four-quadrant gates.

2.4 Effectiveness of Four-Quadrant Gates

Unfortunately, the operational experience with four-quadrant gate crossings in the United States has been extremely limited. This has precluded the collection of statistically significant data and the calculation of four-quadrant gate effectiveness factors in the DOT model. However, the initial safety data has been highly favorable; at the time of this evaluation, no collision between a train and an automobile at a four-quadrant gate grade crossing had occurred in the United States. In its notice of proposed rule making (NPRM) entitled *Use of Locomotive Horns at Highway-Rail Grade Crossings*, FRA proposed estimates of effectiveness rates for various grade crossing treatments, including four-quadrant gates. FRA defined the effectiveness rate as the reduction in the probability of a collision at a grade crossing provided by a supplementary safety measure when compared to the same crossing equipped with conventional automated warning systems of flashing lights, gates, and bells. The effectiveness values for four-quadrant gates are as follows:

Four-quadrant gates without obstruction detection:	0.82
Four-quadrant gates with obstruction detection:	0.77
Four-quadrant gates with medians of at least 60 feet (with or without obstruction detection):	0.92

FRA states that these are highly conservative values based on preliminary measurements. In addition, installing obstruction detection equipment may cause exit gates to remain up indefinitely as one or more vehicles pass over the crossing or platoon through the crossing. Although providing obstruction detection functionality prevents vehicles from becoming trapped within the crossing, probability exists that some motorists will follow violators through the crossing, thereby keeping the exit gates raised. In situations where medians are not installed to prevent this situation, FRA has assumed a lower effectiveness rate.

3. Four-Quadrant Gate with Obstruction Detection Technical Description

The School Street four-quadrant gate system was designed to include the following subsystems: (1) signaling and control, (2) obstruction detection, and (3) warning devices and barriers.

Figure 1 shows a functional diagram of these systems. The primary functions performed by the signaling and control subsystem include the following:

- Train location
- Grade crossing equipment control, such as activation of warning devices, barrier systems, and ODS
- Train control as determined from the operational status of the grade crossing equipment

In the case of the School Street equipment, the grade crossing signaling and control system is interconnected with the Amtrak wayside and in-cab signaling systems. Therefore, any compromise in the integrity of the grade crossing equipment results in a reduction of the signaling aspect and affects railroad operational speeds. If the train engineer fails to respond to a change in signaling aspect, the speed reduction is automatically enforced by the onboard train control system.

The primary functions of the ODS are to detect motor vehicles that are on the grade crossing and determine if they are a hazard to oncoming trains. This provides the two-fold capability of alerting approaching trains to trapped vehicles and releasing the exit gates so that trapped vehicles can escape from the railroad right-of-way. If the sensors detect that the crossing is occupied once all four gates are fully deployed, the control circuitry will cause the exit gates to release. In this manner, trapped motor vehicles are able to safely exit the crossing.

For the School Street system, six inductive loops were installed in the roadway between the tracks and on the roadway approaches to the crossing. Although the sensitivity of the loop system varies, the test team established a minimum detection threshold to reduce the false alarm probability. This threshold equated roughly to detection of metal objects with the cross-sectional area of a motorcycle (500 pounds). If the sensitivity of the loop system were increased, smaller metal objects (i.e., bicycles and shopping carriages), and possibly people, would be detected. This could, however, create an increase in the false alarm probability and be detrimental to railroad operations. These loops are able to detect any metal object weighing over 500 pounds (i.e., a motorcycle). The crossing sensor circuitry is connected to the Amtrak in-cab signaling train control system. If the ODS indicates that the crossing is occupied when a train is within the approach circuit, the in-cab signal aspect will be reduced to a more restrictive state.

The functionality associated with the warning device and barrier subsystems includes (1) warning highway and pedestrian users that a train is approaching the crossing and (2) preventing them from entering the crossing when a train is approaching. At the School Street crossing, the warning devices consist of flashing lights and bells, and the barriers are the four-quadrant gates.

Figure 1 shows a block diagram of the four-quadrant gate system at School Street. The cornerstone of this system is the *Microlok Plus* vital and non-vital control package manufactured by Union Switch and Signal. The vital portion of the Microlok is a microprocessor-based

controller that performs the vital functions of a relay logic interlocking. The non-vital portion, known as the *Genisys* system, is connected to a data logger that is used to record track circuit status, gate position, intrusion of the grade crossing equipment building, crossing flashers status, cab signal status, and the state of the vital microprocessor. Other components that constitute the four-quadrant gate system include the following:

- Reno Agriculture and Electronics (A&E) dual channel programmable menu driven inductive loop vehicle detectors for quad gate railway crossings, Model C-401-R
- Union Switch and Signal highway crossing gate mechanism, Model 950
- Wabtec Vigilant crossing monitor, Model WEM-450
- Harmon Audio Frequency Train Activated Circuit

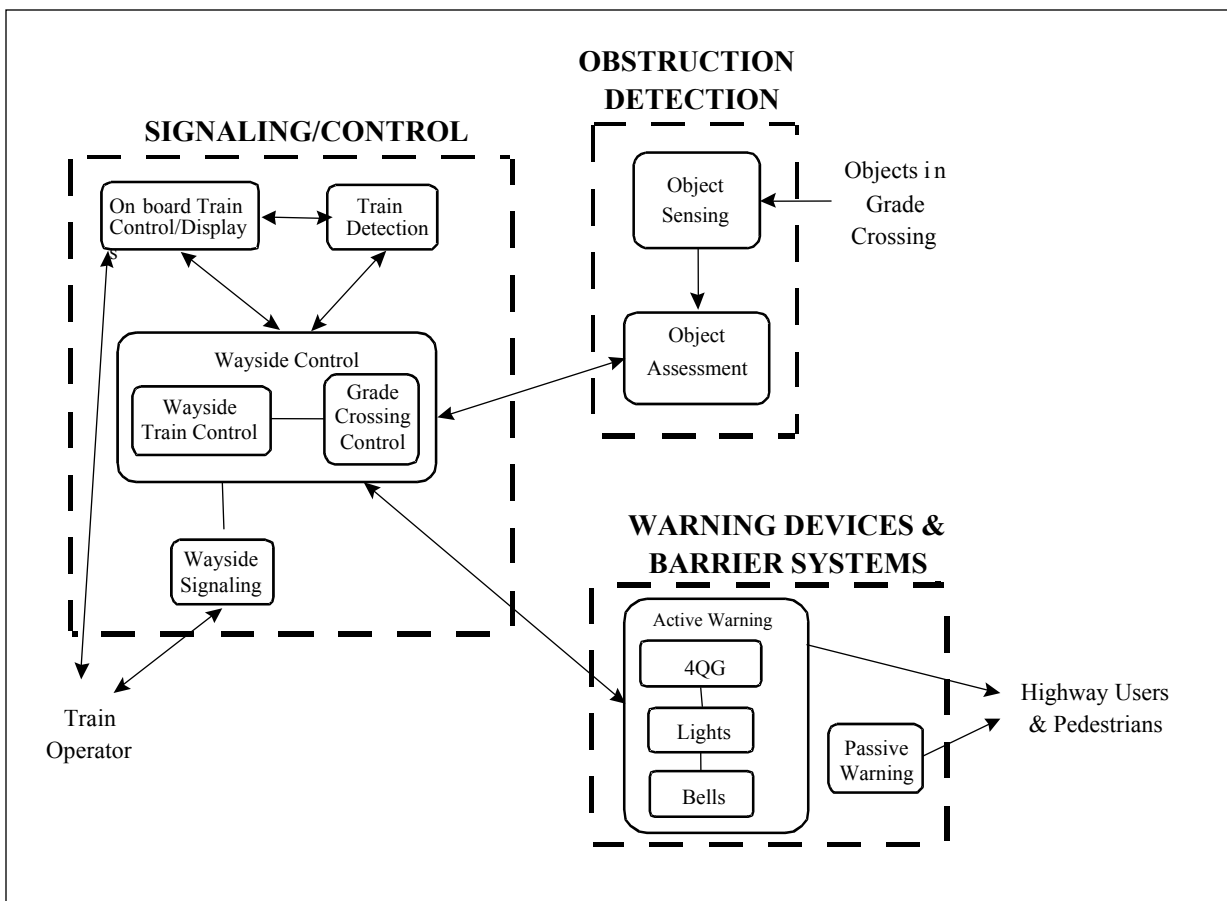


Figure 1. Functional Diagram of the Four-Quadrant Gate/ODS

3.1 General Description

The microprocessor-based controller monitors and controls the two entrance gates and two exit gates. The entrance gates function just like conventional gates employed at dual-gate crossings throughout the United States and are designed to fail in the down or closed position. The exit gates operate in the same manner as the entrance gates but are designed to fail in the up or open

position. The approach circuitry responsible for the activation of the warning devices at School Street is installed at locations 6000 feet west of the grade crossing and 6800 feet east of the crossing, respectively. When these circuits are shunted, the flashing lights and bells are actuated for 7 seconds before the deployment of the entrance gates at the crossing. A 3-second delay is inserted between the deployment of the entrance gates and the exit gates so that vehicles already within the crossing can traverse it safely. Each set of gates requires 5 seconds to achieve full deployment, resulting in a total time from activation of the warning devices to full deployment of 12 seconds for the entrance gates and 15 seconds for the exit gates (Watson, 1998).

Once a train is within the approach circuitry, it is under the supervision of the six inductive loops that comprise the ODS. If the ODS indicates that the crossing is occupied or is not functioning properly, the cab signal aspect will be reduced from *Clear* to *Approach Medium*. If the problem has not been corrected after 10 seconds, the cab signal aspect will be reduced to *Approach*. If the crossing still indicates occupied after a final 10-second interval, then the cab signal aspect will be reduced to *Restricting*. The locations for the reduction of the cab signal aspects were selected such that a braking curve could be achieved to maintain passenger safety and comfort (Watson, 1998).

3.2 Operational States

The normal static condition of the crossing occurs when no trains are on the approach circuitry. In this state, the gates are in the open position, and the lights and bells are deactivated. As a vehicle enters the crossing, the inductive loops detect its presence. The loop status, either unoccupied or occupied, is then transmitted to the microprocessor controller and finally to a data logger. Other parameters that are monitored and recorded include the following:

- Power supply status (on or off)
- Track circuit status
- Relay bungalow door detection and intrusion detection
- Flashing light status
- Cab signal controls

When a train occupies one of the approaches to the crossing, the flashing lights and bells are activated for 7 seconds, and the gates are deployed as described. The gates are deployed by de-energizing the entrance gate control relay and energizing the exit gate control relay. When the train enters the grade crossing island circuit, its presence is detected by the inductive loops but overridden by the microprocessor logic to prevent the cab signaling system from stopping the train. The gates remain closed for a duration of 5 seconds after the train has cleared the crossing. They return to the vertical position through a reversal of the process described above, and the crossing reopens (Watson, 1998).

The microprocessor controller is programmed to perform a health check of the 6 inductive loops every 15 minutes by shunting a test loop buried underneath each loop. This check, however, is executed only if all of the loops have not been activated by motor vehicle traffic within the 15-minute time interval. If they have been activated, the timer is reset. If a loop fails to return to its unoccupied status either after detecting a motor vehicle or being checked by the microprocessor,

the crossing status changes to abnormal. If this condition occurs, the exit gates become disabled, and the cab signaling system is no longer affected by loop or broken gate detection. This information is used to notify maintenance personnel of an equipment malfunction. Once the cab signaling system no longer receives an input from the loops, an automatic reduction in the cab signal aspect occurs, thereby causing an approaching train to initiate braking. In addition, the exit gates remain in the vertical or open position, while the entrance gates are closed (Watson, 1998).

The final condition of the four-quadrant gate system occurs when one or more of the gates become disabled. The microprocessor controller monitors the position of the gates (either up or down) by inputs provided by sensors on the gate arms. If the gates are not deployed within 20 seconds after being activated, they are considered to be broken. This is considered an abnormal condition, and the cab signaling system no longer receives inputs from the crossing equipment (Watson, 1998).

4. School Street Evaluation Plan

4.1 Evaluation Categories

This report presents three evaluation categories: (1) a before and after comparison of motor vehicle driver behavior between the pre-existing dual-gate crossing and the four-quadrant gate crossing; (2) an assessment of the operational performance of the four-quadrant gate system; and (3) user acceptance of the four-quadrant gate technology by locomotive engineers.

The before and after comparison was performed by analysis of train movements captured by a video acquisition system installed at the grade crossing. The pre-existing, or baseline, data was recorded between July 1997 and August 1998. The four-quadrant gate data was recorded from January 1999 through October 2000. Due to the small size of the baseline data set, limited trend analysis was the only realistic option for comparing the safety of the two crossing systems.

The improved safety offered by the four-quadrant gate crossing was determined from analysis of motor vehicle driver behavior captured on video. The white loops shown in Figure 2 were used to activate the video system during times when the train was on approach to the School Street crossing. Multer and Rapoza (1998) studied two types of motor vehicle violations as provided below:

- *Type I:* Motor vehicles traversed the grade crossing after the warning lights began flashing but before the gates were fully deployed.
- *Type II:* Motor vehicles traversed the grade crossing after the gates were fully deployed. For dual-gate systems, the vehicles drove around the gates. For four-quadrant gate systems, the vehicles compromised the gates.

The operational performance of the four-quadrant gate system was assessed through analysis of non-scheduled maintenance calls performed by Amtrak at the crossing for a representative 6-month period. The locomotive engineer acceptance of the technology was characterized by administering a survey to evaluate their experience and reactions as users of the crossing.

4.2 Observational Setting

Figure 2 illustrates the four-quadrant gate/ODS (hereon referred to as the four-quadrant gate system) at School Street. As described in an Amtrak report, the system is designed to provide a warning time of 65 to 79 seconds depending upon the direction of train travel (Watson, 1998). The entrance gates installed in the driving lane of traffic and the exit gates installed in the reverse driving lane provide a visual deterrent for motor vehicle operators and keep them from entering the railroad right-of-way. The entrance gates are designed to fail in the deployed or down position (normal railroad operating procedures), and the exit gates are designed to fail in the open or up position. With this type of system, motor vehicle traffic is prevented from circumventing deployed gates during a train movement and cannot become trapped within the highway-rail crossing.

The evaluation site is a bi-directional, two-track grade crossing, located in the town of Groton, CT, at milepost 131.50 of the NEC system. It is a public crossing and functions as the only

access point to the 27-acre Willow Point section of Groton. Although primarily a residential area surrounded by Mystic Harbor and Long Island Sound, Willow Point is also home to several businesses, including three recreational boat clubs. The majority of highway traffic through the crossing consists of private motor vehicles. However, during the summer, hundreds of boats are hauled through the 25 ft (7.6 m) wide crossing. The most recent measurement of annual average daily traffic (AADT) volume at the School Street crossing was 900 vehicles. Two railroads, Amtrak and the Providence and Worcester Railroad, operate within a range of 15-20 train movements through the crossing per day (FRA, 1993). Before the installation of the four-quadrant gate system, the maximum train speed through the crossing was 70 mph (113 km/h), with a speed restriction of 55 mph (89 km/h), 1600 ft (488 m) east of the crossing for the Mystic River movable bridge. Although the maximum train speed through the crossing has not been increased since the implementation of the four-quadrant gate system, Amtrak has long-term plans to increase the speed to 80 mph (129 km/h). In 2000, a four-quadrant gate system was installed at the nearby Palmer Street crossing in Stonington, CT. Subsequently, FRA permitted an increase in the civil speed to the maximum allowable limit of 90 mph (145 km/h) from 80 mph (129 km/h) at that location.

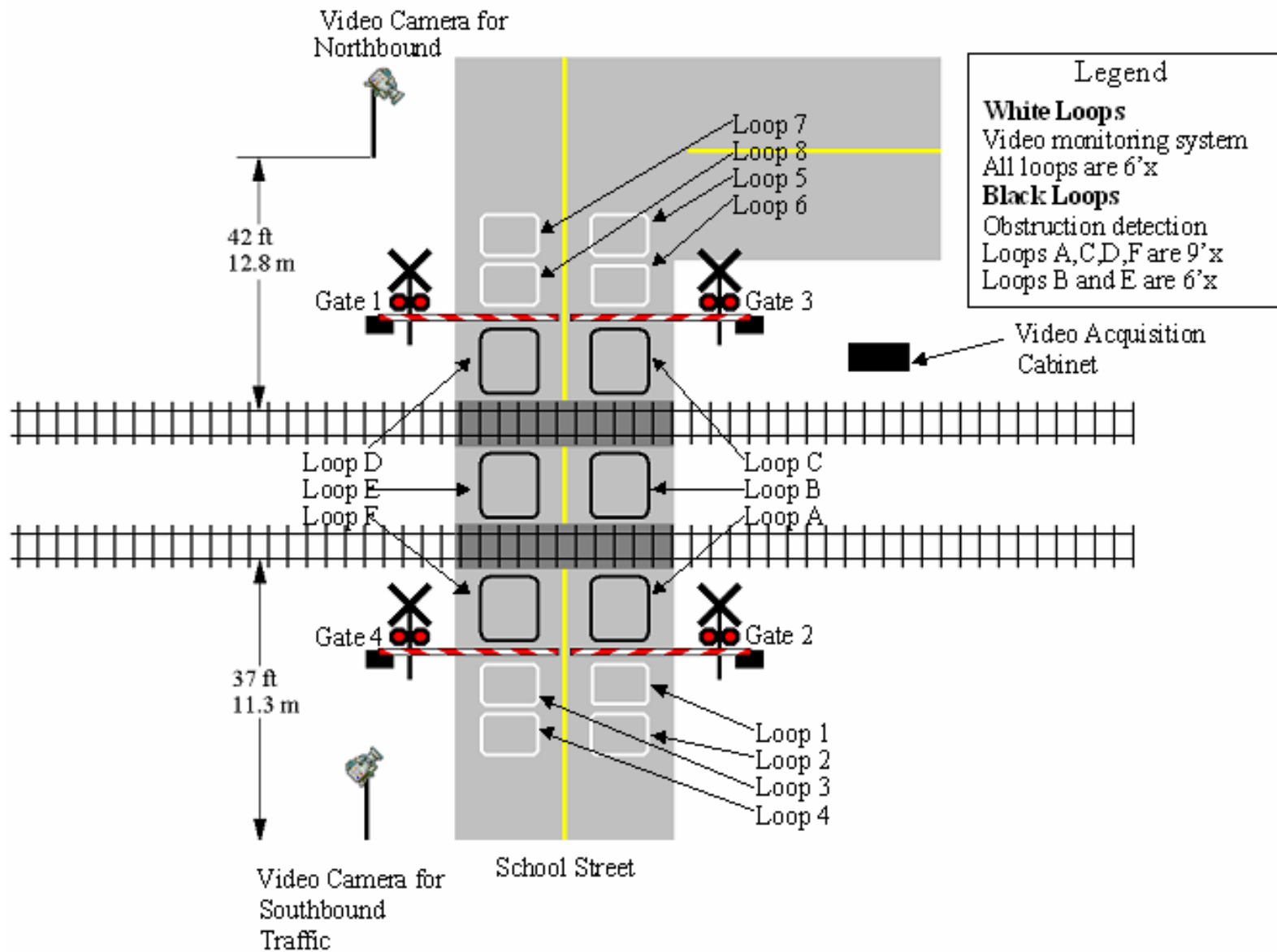


Figure 2. Layout of the School Street Four-Quadrant Gate and Video Acquisition Systems

4.3 Motor Vehicle Violation Data Collection and Reduction

Figure 2 shows the video acquisition system. This configuration consisted of two black and white cameras with infrared lights mounted on utility poles on opposite sides of the right-of-way. In tandem with the video acquisition system was a set of inductive detection loops for highway traffic counts (unrelated to the ODS loops) embedded in the roadway outside of the gate arms.

Each video train movement was recorded from the time the approach circuit was shunted until the train arrived in the field of view, up to a maximum of 120 seconds. Video data were transmitted to a wayside computer cabinet and underwent digital to analog processing before being stored. Once the train movements were completely recorded, the data was transmitted by modem to a playback computer system at the Volpe Center. For every crossing approach circuit activation, the video acquisition system captured the following fields:

- Time of event (military time)
- Length of video event (seconds)
- Type of train (passenger, freight, construction, or maintenance)
- Direction of train travel (east or west)
- Track (1 or 2)
- Whether the gates deployed as expected (yes or no)
- Whether the gates redeployed as expected (yes or no)
- Type I violations (number of motor vehicles)
- Type II violations (number of motor vehicles)

4.4 Operational Performance

The operational performance of the four-quadrant gate system was assessed through analysis of non-scheduled maintenance calls performed by Amtrak at the crossing for a representative 6-month period. Although this was not the most exact method for assessing the reliability performance of the crossing technology, the approach was appropriate for two reasons. First, no long-term reliability data are available for this type of technology; however, given its similarity to conventional dual-gate grade crossing technology, no significant differences are expected in their reliability. Second, the amount of time required to collect statistically significant reliability data was well beyond the scope of the School Street evaluation.

4.5 Locomotive Engineer Acceptance

Locomotive engineer acceptance of the technology was characterized by administering a survey to evaluate their experience and reactions as users of the crossing. Since the four-quadrant gate crossing was implemented as a prototype technology, the locomotive engineer survey was employed to incorporate user feedback for fine-tuning the design of the School Street crossing.

4.6 System Deployment Cost

The system deployment cost was evaluated under the umbrella of the following broad categories:

- Direct labor: Costs incurred for actual labor unburdened by overhead.
- Additional labor costs: All additional labor costs, including benefits, overhead, material handling, travel, and per diem, as well as general and administrative costs.
- Engineering services: Professional engineering services provided by Amtrak for design of the four-quadrant gate crossing.
- Material cost: Includes items, such as the crossing controller, vehicle detection system, light emitting diode (LED) flasher units, and entrance and exit gate mechanisms.
- Equipment cost: Equipment expenditures associated with the installation of the four-quadrant gate crossing, such as construction equipment.

5. Results and Discussion

5.1 Before and After Comparison

The video data sets for the pre-existing dual-gate and the four-quadrant gate systems were normalized for gate activations in which the grade crossing approach circuitry was shunted and motor vehicles were present at the crossing. For each of these train movements, the motor vehicle violations were tabulated and classified as either Type I or Type II, as shown in Table 2. The violation rates per 100 train movements in Table 2 were computed as follows:

$$\text{Normalized Type I Violations} = \frac{\text{Type I Violations}}{\text{Total Number of Train Movements}} \times 100 \quad (1)$$

$$\text{Normalized Type II Violations} = \frac{\text{Type II Violations}}{\text{Total Number of Train Movements}} \times 100 \quad (2)$$

For the pre-existing dual-gate crossing, 56 train movements between August 1997 and July 1998 were captured on video. Of those movements, nine showed no vehicles present, thus resulting in the 47 train movements in the before condition. Similarly, for the four-quadrant gate system, 4,182 train movements between January 1999 and February 2000 were evaluated. From that data set, 1,632 were filtered out because no vehicles were present, yielding a data set of 2,550 train movements for the after condition.

These results show that the Type I (59.57) and Type II (166.00) violation rates per 100 train movements were significantly higher when the dual-gate crossing was placed in service than after the implementation of the four-quadrant gate system (25.88 and 0.00). In addition to the four-quadrant gate data exhibiting a shift of all the motor vehicle violations from Type II to Type I, fewer average motor vehicle violations occurred once the four-quadrant gate system was placed in service. These results indicate that the four-quadrant gate technology produced a decrease in the risky motor vehicle driver behavior at the School Street crossing. This was noteworthy given that the average warning time measured at the crossing was 80 seconds and that the percentage of Type II violations at dual-gate crossings increases significantly for warning times above 35 seconds (Fitzpatrick et al., 1997). Given that the average warning time measured at the crossing was 80 seconds, the reduction in Type II violations at the four-quadrant gate crossing was considerable.

For a significant number of the train movements in the dual-gate data set shown in Table 2, the video acquisition system timed out before a train passed through the crossing. The original design of the video monitoring system was to record until a train appeared at the crossing, for a maximum time of 2 minutes. However, a substantial portion of the before video acquisition program coincided with electrification of the NEC in Connecticut. This increased the likelihood that construction and maintenance vehicles within the approach circuit had activated the grade crossing circuitry during the train movements in which the video acquisition system timed out. In fact, construction activity at the crossing became so regular that the video acquisition system

was disconnected completely for two intervals of 4 and 2 months, respectively. This was the reason for the relatively small sample size for the before data as compared to the after data.

Table 2. Vehicle Violations at the Four-Quadrant Gate System as Compared to the Dual-Gate System

	Number of Train Movements	Vehicle Violations		Vehicle Violations per 100 Train Movements	
		Type I	Type II	Type I	Type II
Dual-Gate	47	28	78	59.57	166.00
Four-Quadrant Gate	2550	660	0	25.88	0.00

When only movements with motor vehicles and trains present were analyzed, the sample size decreased substantially, as shown in Table 3. The Type I (85.19) and Type II (3.70) violation rates per 100 train movements for the dual-gate system were substantially higher than for the four-quadrant gate system (25.88 and 0.00). These results appeared to further corroborate this report’s conclusion that the four-quadrant gate technology produced an overall decrease in the risky behavior of motorists at the School Street crossing.

Table 3. Vehicle Violations at the Four-Quadrant Gate System as Compared to the Dual-Gate System, with Motor Vehicle(s) and Train Present

	Number of Train Movements	Vehicle Violations		Vehicle Violations per 100 Train Movements	
		Type I	Type II	Type I	Type II
Dual-Gate	27	23	1	85.19	3.70
Four-Quadrant Gate	2128	456	0	21.43	0.00

Heathington et al. (1989) used a slightly different definition of gate violation described as follows: a motorist either drove around a gate in the down position or collided with the gate as it was closing. This is consistent with the Type II violation definition found in Section 5.1. The results of this study showed an average of 2.6 violations per train movement in the dual-gate configuration and 0.0 violations in the four-quadrant gate system. In the dual-gate configuration, this equates to 266 violations per 100 train movements, substantially higher than the results found in Tables 2 and 3. This was most likely because of the substantially higher AADT (14,000) at the crossing in the Heathington study given roughly the same number of trains per day. In addition, the roadway in the Heathington study was four lanes wide as compared to only the two lanes at the School Street crossing. This was consistent with the work by Abraham et al. (1998) showing that multitrack crossings at multilane highways experienced the highest incidence of motor vehicle violations.

The results of the Los Angeles LRT study at the 124th Street crossing also reflect the findings of this research. Before the four-quadrant gate/ODS was installed, the Type II violation rate was 0.26 Type II violations per 100 train movements. After the system was installed, the Type II violation rate decreased to 0.15 per 100 train movements, a 94 percent reduction (LACMTA, 2000).

The Type I violation rates were also analyzed for seasonal fluctuations. A representative month from each season was selected, as shown in Table 4. This was reflected in the relatively small data set collected during the fall of 1999. These values were normalized in terms of violations per 100 train movements, as illustrated in the last column of the table. Although it might be expected that little variation would exist in the number of train movements per day, several factors contributed to the discrepancies between the months. First, the total number of train movements for each month was the resultant of a filtering process. The filter was used to exclude movements in which the gates never deployed, and construction or testing of the warning device systems was thought to have occurred. These movements were considered not to be indicative of normal operations at the crossing. This was especially true of the fall data set, which underwent the highest amount of data reduction and filtering. Second, the previously mentioned construction and maintenance activities in the School Street vicinity may have occurred disproportionately during certain months.

Table 4. Four-Quadrant Gate Seasonal Activity

Season	Months	Monthly Number of Days	AADT	Number of Train Movements	Normalized Daily Train Movements
Winter 1999	Jan-Feb	28	570	497	17.75
Spring 1999	April	24	908	427	17.79
Summer 1999	July	29	1,062	473	16.31
Fall 1999	Oct-Nov	13	662	232	17.85

Applying Equation (1) to the train movement and vehicle violation data in Tables 4 and 5, the Type I average seasonal violation rates shown in Table 5 were calculated. Excluding the data set from the summer of 1999 (11.42), fairly close agreement was shown among the violation rates. This result was interesting since the School Street crossing experienced the highest average daily traffic (ADT) of 1,062 motor vehicles during the month of July. In contrast, the high fall and winter violation rates of 21.12 and 17.10 per 100 train movements were recorded during periods of lower ADT at the crossing; 662 and 570 vehicles, respectively. One possible explanation for the lower July violation rate is that motorists may have been less inclined to violate the grade crossing during periods of peak usage or when they were towing their boats to the marina and therefore would have incurred a higher personal risk of loss of property. In addition, summer visitors to the area may be less familiar with the crossing and therefore less likely to intentionally commit a violation.

Table 5. Four-Quadrant Gate Seasonal Type I Violation Rates

Season	Month	Number of Vehicle Violations	Vehicle Violations Per 100 Train Movements	Normalized for Daily Traffic Moment
Winter 1999	Jan-Feb	85	17.10	3×10^{-4}
Spring 1999	April	76	17.80	1.96×10^{-4}
Summer 1999	July	54	11.42	1.08×10^{-4}
Fall 1999	Oct-Nov	49	21.12	3.19×10^{-4}

As further evidence, the August violation rate was found to be extremely close to the July value. This hypothesis was supported by data that showed summer was the peak season for ADT and traffic queues at the crossing. Additionally, the fall and winter months, which experienced the highest average violation rates, had the lowest ADT and traffic queues at the crossing.

The results from this analysis were verified by normalizing the average daily violation rate for traffic moment as shown in the following equation:

$$\text{Normalized Daily Violation Rate} = \frac{\text{Daily Violation Rate}}{\text{Daily Traffic Moment}} \quad (3)$$

where Daily Traffic Moment equals number of train movements per day multiplied by ADT.

The results of these calculations, shown in the last column of Table 5, still indicated that July exhibited the lowest average monthly violation rate.

For comparison, Table 6 shows a sampling of the seasonal Type I and Type II violation rates per 100 train movements for the dual-gate system. This analysis was performed using baseline data collected during the months of February and April, and the first three weeks of July 1998. Beginning July 20, 1998, the four-quadrant gate system became active, thus precluding the analysis of any fall seasonal violation data. The trend analysis of the data indicates that the average violation rates were weighted towards the riskier driver behavior associated with Type II violations as shown previously. The July data exhibited the lowest violation rates of the 3 months and increased support for the theory that motorists were engaging in less risky behavior during the summer when personal property loss may be of concern.

Table 6. Dual-Gate Seasonal Type I and Type II Violation Rates

Season	Month	Number of Train Movements	Motor Vehicle Violations		Vehicle Violations Per 100 Train Movements	
			Type I	Type II	Type I	Type II
Winter 1998	February	7	3	11	42.86	157.14
Spring 1998	April	9	3	17	33.33	188.89
Summer 1998	July	5	1	6	20.00	120.00
Fall 1998	N/A	N/A	N/A	N/A	N/A	N/A

The motor vehicle violation data of the four-quadrant gate crossing was also analyzed in terms of the Type I violation frequencies for different hourly periods. The data sets used in the seasonal violation analysis were sorted in terms of time of day and divided into the hourly periods shown in Table 7. This type of analysis has been employed as a reliable method of characterizing the violation rates between different hours of the day at crossings (Coleman and Venkataraman, 2001). These results showed that the highest level of Type I violation activity occurred between the hours of 9:00 a.m. and 3:00 p.m. This type of driving behavior indicates that more people were driving over the grade crossing for personal or leisure travel activities rather than activities associated with commuting back and forth to work. If the crossing had been used more for commuting purposes, then the violation values for the traditional peak commuting hours of 6:00 a.m. to 9:00 a.m. and 3:00 p.m. to 6:00 p.m. would have experienced the highest Type I violation levels.

Table 7. Four-Quadrant Gate Hourly Type I Rates

Time Periods	Number of Type I Vehicle Violations
6:00 a.m.–9:00 a.m.	27
9:00 a.m.–12:00 p.m.	60
12:00 p.m.–3:00 p.m.	76
3:00 p.m.–6:00 p.m.	46
6:00 p.m.–9:00 p.m.	29
9:00 p.m.–12:00 a.m.	14
12:00 a.m.–6:00 a.m.	12

The Type I violations were also classified by train type as listed in Table 8. The category “video timed out” refers to a normal train movement that lasted longer than the 2-minute maximum time of the video acquisition system. The results showed that the highest number of Type I (17.86) violations per 100 train movements was associated with construction and maintenance trains. This outcome may have been skewed since maintenance and construction trains primarily operated during the overnight hours, when revenue service was at a minimum and motor vehicle drivers were more likely to engage in Type I violation behavior.

Table 8. Four-Quadrant Gate Type I Violation Events and Vehicle Violations as a Function of Train Type

Train Type	Number of Train Movements	Type I Vehicle Violations	Vehicle Violations per 100 Train Movements
Passenger	1,270	198	15.59
Freight	29	2	6.90
Construction/Maintenance	28	5	17.86
Video Timed Out	302	59	19.54

5.2 Warning Time Analysis

Since the School Street crossing does not have constant warning time functionality, the warning times at the crossing varied widely depending on train speed as shown in Figure 3. The Federal minimum warning time requirement is 20 seconds. However, the State of Connecticut requires an even more stringent warning time of 30 seconds. The School Street system was designed for a warning time range of 65-79 seconds (depending on the approach direction) and exhibited an average warning time of 80 seconds, right on the higher end of the operating requirement. As can be seen, the majority of the train events had warning times above 60 seconds. Previous research on dual-gate crossings (Heathington et al., 1989) has shown that, for warning times of 60 seconds and beyond, motorists tend to drive around the closed gates, with more motorists committing violations as the warning time increases. This trend is also indicative of grade crossings with highly variable warning times, such as the School Street crossing. The four-quadrant gates, however, eliminated any associated violations.

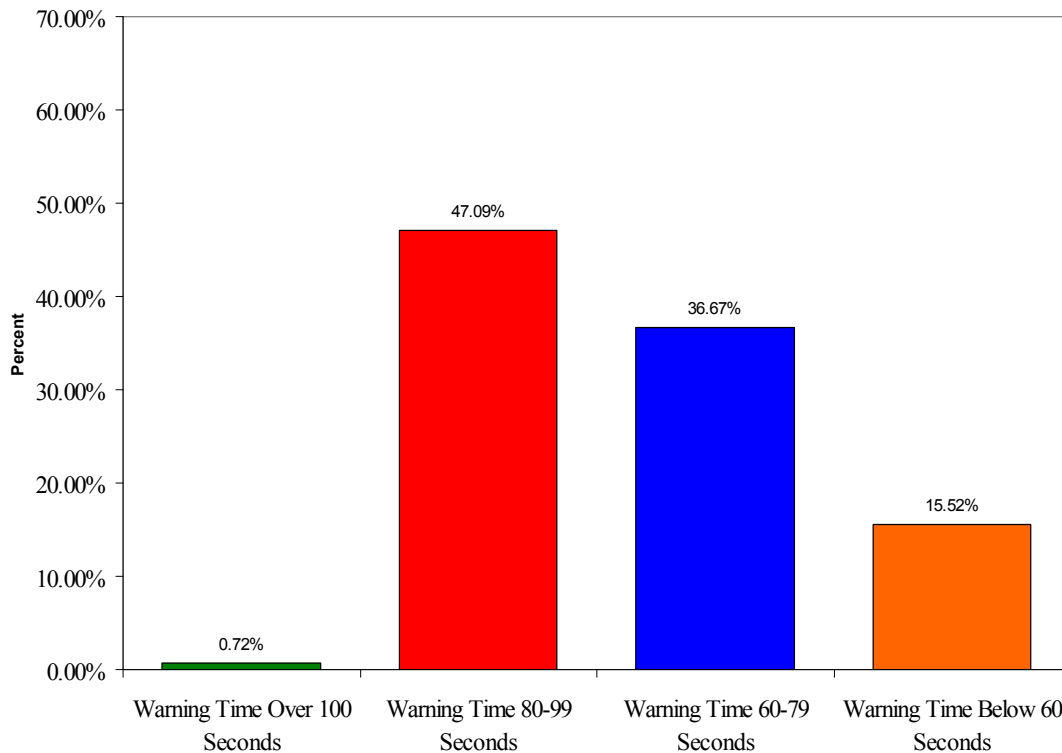


Figure 3. Distribution of Gate Warning Times for Four-Quadrant Gate Crossing System

The extended warning time at the School Street crossing is a function of the overall grade crossing design. As described in Section 3, the long eastbound and westbound approaches are required to encompass the safe braking profile of a high-speed passenger train in the case of a trapped vehicle or any other type of compromise to the crossing. Constant warning time devices have since been successfully implemented at other four-quadrant gate crossings in the Connecticut corridor. In addition to the inherent constant warning time benefit these devices provide, the added benefit of less variability in warning time has been shown to yield a decrease in motor vehicle violations.

5.3 Operational Performance

Since the four-quadrant gate crossing became operational in late July 1998, no unusual characteristics in the system performance were observed. However, Amtrak instituted several design changes to improve the capability of this demonstration technology during the first several months of system operation. It is worth noting that numerous construction and maintenance activities associated with the electrification and augmentation of the NEC infrastructure for high-speed rail were occurring within the general vicinity of the School Street crossing.

One of the primary design improvements was related to the location of the control circuit (CC) sign at the Mystic, CT, Amtrak train station. The westbound grade crossing approach circuit located east of the crossing overlapped with the westbound train berth at the Mystic, CT, Amtrak station. Some westbound Amtrak trains making stops at Mystic were inadvertently activating the School Street grade crossing circuitry, thereby causing the warning system and gates to be activated. This issue was resolved within the first 2 months of system operation when Amtrak installed a CC sign as a stopping point for westbound trains (Williams, 1998).

During the first year of operation, the video acquisition system captured numerous events in which construction and maintenance activities were occurring at the School Street crossing. As stated earlier, these activities were primarily related to electrification work and the upgrading of the in-cab signaling system to which the four-quadrant gate system was interfaced. As such, extended periods of time may have been required to complete these projects. Although a best effort was made to minimally impact revenue service operations, it is probable that some of these construction and maintenance activities did result in unwanted grade crossing operations. Two indirect measures of the effect of the construction and maintenance activities were the number and duration of the police calls to the crossing by the Groton police department. For the 8 months of dual-gate operation before the installation of the four-quadrant gate system, 7 extended gate down times were recorded. These events ranged from 8 to 74 minutes, totalling 212 minutes. These times were recorded beginning with the dispatch of the patrol officer to the crossing to the time the crossing was cleared and reopened for service. For the 17 months after the installation, police officers were called to the crossings 26 times for extended gate down times. These events ranged from 1 minute to 4 hours and 32 minutes, totalling 870 minutes.

A list of non-scheduled maintenance calls to the crossing for a representative post-evaluation 6-month period was obtained from an FRA Region I staff report (Sottile, 2001). Of the 18 maintenance calls documented by Amtrak during the period, 39 percent (7/18) were not attributed to a specific grade crossing failure and may have been false alarms. Additionally, 64 percent (7/11) of the remaining 11 maintenance calls were caused by maintenance-of-way equipment and revenue service trains occupying the grade crossing approach circuit for excessive amounts of time. Although these movements may have produced extended gate activations, no situation arose indicating that the crossing was not functioning as designed. These maintenance calls should be attributed to rail operational issues instead. The four maintenance calls that actually required repair of malfunctioning equipment were unrelated to the architecture of four-quadrant gate technology. One of these, loss of commercial electric power, likely did not result in a failure of the grade crossing system since a backup power supply

was at the crossing. The other three were described as relay base loose, loose contact wire in gate mechanism, and defective track circuit.

5.4 Locomotive Engineer Survey

A locomotive engineer survey was administered to Amtrak engineers to characterize their experience and reactions as users of the School Street four-quadrant gate crossing. The response rate for this survey was 55 percent (11/20), and the engineers were enthusiastic about being asked for feedback. The results of the survey showed that 91 percent (10/11) of the respondents considered their understanding of the four-quadrant gate system as good or very good and that technical training was not required. Additionally, 100 percent (10/10) of the engineers who answered the question stated that no changes were required in their train-handling strategy upon entering the island circuit of the crossing. Finally, 73 percent (8/11) of the respondents stated that the four-quadrant gate system (as compared to the pre-existing dual-gate system) had reduced their anxiety level at the School Street crossing.

The primary suggestion given by the locomotive engineers was to install the previously discussed CC sign at the crossing approach circuit located west of the Mystic, CT, Amtrak station. This sign, installed in October 1998, was used as a stopping point for westbound Amtrak trains and further increased the performance of the four-quadrant gate system by producing more consistent warning times at the crossing.

5.5 System Deployment Cost

Since the four-quadrant gate crossing is a new system, sufficient data are not available for determining system life-cycle costs. However, ConnDOT and Amtrak submitted system invoices for deployment of the School Street crossing to the Volpe Center. From this information, the non-recurring engineering, system procurement, and installation costs were extracted and documented in this report.

FRA, in a unique cost-sharing agreement with the State of Connecticut, was able to finance 80 percent of the program cost in the form of a Federal grant to the State. Financing was made available from the National Highway Trust Fund by means of the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991. Under ISTEA, the U.S. DOT “may award contracts and grants for demonstrations to determine the contributions that high-speed ground transportation could make to more efficient, safe, and economical intercity transportation systems.” Additionally, the U.S. DOT can fund a maximum of 80 percent of the cost for any project under agreement. The ISTEA legislation states that the remaining funding should be provided by private industry to the maximum extent possible. However, the State of Connecticut financed the remaining 20 percent of the cost for the demonstration program in a unique public-private partnership with Amtrak.

The two primary contractors for the project were Amtrak and Union Switch and Signal (US&S). Amtrak was paid under the auspices of the 80/20 grant described above, which had Federal and State funding limits of \$800,000 and \$200,000, respectively. As shown in Table 9, the total 80/20 grant expenditure was \$922,200; the total FRA outlay was \$737,800. Total system deployment expenditures amounted to \$731,000. The other expenses shown include \$67,500 for

Grant Administration by ConnDOT and a payment of \$124,000 to Asea Brown Boveri, Ltd. (ABB) for initial engineering consultation on the program.

In addition to the 80/20 grant program, FRA funded US&S to modify the wayside technology used in the Microlok microprocessor for approximately \$125,000. Table 10 shows this cost and the final program cost of \$1,047,200. Of this total cost, FRA funded approximately \$863,000 or 82 percent.

The expenditures are limited to the information presented in Tables 9 and 10 and are not sufficiently refined to be separated into recurring and non-recurring engineering costs. ConnDOT has estimated, however, the four-quadrant gate technology to have recurring engineering or duplication costs of approximately \$400,000. This value is approximately 40 percent of the initial system expenditure (Szgedy, 2002).

Table 9. Expenditures for ConnDOT/FRA Grant

Cost (\$) Category	Amtrak	ConnDOT Grant Administration	Payment for Engineering Services to ABB	Subtotal by Government Agency
FRA	584,800	53,800	99,200	737,800
ConnDOT	146,200	13,400	24,800	184,400
Subtotal by Cost Category	731,000	67,200	124,000	
Total	922,200			

Table 10. Total Project Expenditures

Cost (\$) Category	80/20 Grant	FRA Grant with US&S	Subtotal by Government Agency
FRA	737,800	125,000	862,800
ConnDOT	184,400		184,400
Total Expenditures	1,047,200		

6. Recommendations and Lessons Learned

The following are recommendations from the evaluation of the four-quadrant gate/ODS demonstration based on lessons learned.

6.1 Benefit Analysis to Support Effectiveness Values of Four-Quadrant Gates

In the Locomotive Horn NPRM, FRA states that the estimates of effectiveness for four-quadrant gate systems are conservative. Because of the limited experience in the United States with four-quadrant gate systems, it has been difficult to accurately quantify the effectiveness values for this technology. Most of the data that has been collected was obtained from the two four-quadrant gate systems installed under the North Carolina Sealed Corridor program. As with School Street, this study measured the reduction in gate violation rates, not the actual changes in train-motor vehicle collisions. As such, it is very difficult to correlate the relationship between gate violations and collision risk for determining the effectiveness value of a grade crossing treatment. This has been a topic of discussion within the grade crossing safety industry because of the concern that this type of analysis will either lead to an over- or under-estimation of grade crossing collision risk.

The authors of this report recommend a benefit study to characterize the true effectiveness of four-quadrant gate crossings. One measure that is often used to estimate the effectiveness of grade crossing treatments is the increase in the average number of seconds before the arrival of a train at a crossing in which violations occur. To date, little research supports the correlation between these close-call collision events involving trains and motor vehicles. However, empirical data from grade crossing accident reports suggest that most collisions arise from motorists attempting to circumvent grade crossings. If this is the case, then crossings with higher than average close-call collision events will benefit from four-quadrant gate systems.

The type of study recommended above is best performed using the before and after approach of baselining supposed high-risk crossings in terms of close-call collision events, motorist behavior, and measuring the reduction resulting from four-quadrant gates. This type of research will support FRA efforts to better quantify the effectiveness of four-quadrant gate systems and may eventually lead to more widespread implementation of this technology.

6.2 Comparison of Four-Quadrant Gate Systems with and without Obstruction Detection Functionality

As stated previously, FRA is collecting data in support of the rulemaking process for locomotive horns. The proposed rulemaking contains estimated four-quadrant gate effectiveness values for systems with and without obstruction detection. However, these values are only estimates and have not been corroborated with actual data. Experience in the United States with four-quadrant gate technology has been so limited that little real data exists to substantiate any of the effectiveness values documented in the Locomotive Horn NPRM. A long-term study of four-quadrant gate technology with and without obstruction detection functionality is recommended to determine better-defined effectiveness values.

The basis for this discussion is that ODSs possess inherent properties that may increase the risk of train-vehicle collisions under certain conditions. The Locomotive Horn NPRM discusses two such conditions. One relates to the coordination of roadway traffic signals with four-quadrant gates. For example, a stop sign at one end of a crossing may result in a queuing of vehicles onto the crossing itself. In this case, the ODS would keep the exit gates open to allow motor vehicles to clear the crossing. This action could potentially result in the exit gates remaining open for an indeterminate amount of time as motor vehicles traverse the crossing. In a similar vein to the scenario described above, the second condition pertains to the exit gates remaining open in the event that a motor vehicle becomes trapped on a crossing. This functionality could possibly be used by the platooning of motor vehicles to keep the exit gates open for an indefinite amount of time as they weave around the entrance gates. Thus, one potential concern is the mitigation of the benefits derived from obstruction detection technology and an increased risk of train-vehicle collisions.

6.3 Data Collection Conditions

As discussed previously, a significant amount of the data was collected under less than ideal conditions and was therefore difficult to analyze without filtering. This process resulted in a small before data set from the dual-gate crossing system. Two issues, one recurring and the other systemic, mitigated the effectiveness of the before data collection process. First, significant activity from railroad construction and equipment frequently occurred within the vicinity of the School Street crossing. This activity was associated with the installation of the overhead catenary system for upgrading the North End of the NEC to electrified territory and the overall improvement of the track infrastructure and signaling system. Much of this equipment consisted of high-rail vehicles and construction trains that were operating within the approach circuitry of the grade crossing and causing activation of the grade crossing warning devices and gates. During certain periods, the construction activity was so frequent that the video data acquisition system was shut down until the activity decreased.

The other factor that was the cause for less than ideal conditions during the before data collection stage was the video data acquisition system itself. This system was designed only to operate during situations in which both the grade crossing circuitry was activated and a motor vehicle was traversing the crossing. This type of system precluded the analysis of parameters other than motor vehicle violations, such as vehicle queues, trains per day, and train type. A more sophisticated video acquisition system was used during the after data collection period. This system was installed at the same time as the four-quadrant gate system and was capable of recording all approach circuitry activations, regardless of the presence of motor vehicles.

6.4 Develop Standard Format for Tracking How Grant Money Is Allocated

When a State receives a grant from FRA, no mechanism is in place that describes to what level of detail should be documented. In the case of the School Street program, the costs were delineated in the broad categories of engineering, railroad forces (including labor), and grant administration. This made it difficult to separate the variable, or recurring, costs from the fixed, or non-recurring, costs. Recurring costs refer to expenditures that continue well after a project has been deployed and entered service. These include as a minimum costs associated with the operations and maintenance of the equipment. Non-recurring or fixed costs are associated with

engineering that occurs at or near the beginning of a project. These are one-time outlays and do not occur again during the lifetime of a project and could be amortized over the life of the system. Two examples include research and development and capital investments for equipment procurement and installation.

The collection and characterization of cost data are important in several respects. Cost data are used to approximate life-cycle costs of projects, to provide inputs in benefit-cost analyses for planning and trade-off studies, and to evaluate the effectiveness of new technology.

The authors recommend that, as a minimum, recurring and non-recurring costs should be tabulated by State DOTs. Other costs that may be of value include the following:

- Government, commercial, and consumer
- Sunk or legacy system
- Shared
- Private partner
- Cost baseline and base year

7. Conclusions

The results of this investigation were extremely favorable in terms of the safety benefits and operational performance provided by the four-quadrant gate system. A comparison of the four-quadrant gate and the pre-existing dual-gate crossing systems was performed by assessment of video data collected during a 3-year period. The analysis showed that the four-quadrant gate technology provided an increase in motor vehicle driver safety performance at the School Street crossing, given similar exposure levels. The primary supporting evidence for this conclusion was the 100 percent reduction in the riskier Type II violations by motorists at the four-quadrant gate crossing, compared with Type II violations at the pre-existing dual-gate crossing system. Furthermore, the four-quadrant gate system yielded a decrease in the frequency of Type I violations.

A similar comparison of the seasonal violation rates for the School Street crossing substantiated the conclusion that the four-quadrant gate system precipitated a decrease in the risky behavior of motorists. In addition, motorists exhibited the least risky behavior during the summer in spite of the fact that it was the peak season for motor vehicle traffic and traffic queues.

The analysis of the hourly violation rate for the four-quadrant gate system found the midday hours to be the highest. In contrast, the standard commuting hours of 6:00 a.m. to 9:00 a.m. and 6:00 p.m. to 9:00 p.m. yielded considerably lower violation rates. This type of driving behavior indicates that more people were driving over the grade crossing for personal or leisure travel rather than travel associated with commuting back and forth to work. A complementary analysis by train type found that maintenance-of-way and construction trains produced the highest violation rates.

The analysis of the operational performance of the School Street four-quadrant gate system indicates that the technology performed as designed and required few post-installation modifications. The most likely cause of highway delays from extended gate activations was found to be maintenance-of-way railroad vehicles and revenue service trains occupying the grade crossing approach circuits for long periods of time. This was an operational concern and not an issue exclusive to the design of four-quadrant gate crossings with this architecture.

The survey of Amtrak locomotive engineers who operated trains through the crossing provided positive user acceptance of the four-quadrant gate system. In the survey, the locomotive engineers stated that the four-quadrant gate system reduced their anxiety level and did not impact their train-handling capability.

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Appendix



STATE OF CONNECTICUT DEPARTMENT OF TRANSPORTATION

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September 26, 2001

Mr. Peter Montague
Chief, Systems Analysis Division
Office of Railroad Development
U.S. Department of Transportation
Federal Railroad Administration
400 Seventh Street, S.W.
Washington, D.C. 20590

Dear Mr. Montague:

Subject: Demonstration Program Report
School Street, At-Grade Crossing
FRA No. DTFR53-94-G00004

The Connecticut Department of Transportation is pleased to transmit to you the **Final Report** of the successful Quad Detection and Automatic Train Control demonstration recently completed at School Street at-grade crossing in Groton (Mystic), Connecticut. We believe that this satisfies our obligations concerning the Grant for this demonstration and the operation of the advanced warning safety system.

Along with FRA and Amtrak, we take great pride knowing that this accomplishment will have far reaching positive implications in the area of railroad safety.

Very truly yours,

A handwritten signature in black ink, appearing to read "M. Neri".

Mark D. Neri
Assistant Rail Administrator
Bureau of Public Transportation

Enclosure

cc: Mr. Michael T. Saunders

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School Street Quad Gate Crossing With Vehicle

Detection and Automatic Train Control

National High Speed Ground Transportation Technology

Demonstration Program

Federal Railroad Administration (FRA) Number: DTFR53-94-G00004

Connecticut, Department of Transportation (CDOT) number: 0058-0260

School Street Crossing is located on the National Railway Passenger Corporation (Amtrak) Northeast Corridor (NEC), at milepost 131.2, Groton (West Mystic), Connecticut.

Prepared by: Stephen R. Szegedy, Project Concept Designer, Project Manager of the Bureau of Public Transportation, Connecticut Department of Transportation.

Introduction

The crossing is public and provides the only access to a 27-acre residential/commercial neighborhood surrounded by Mystic Harbor and Long Island Sound. In the area accessed by the crossing, there are 36 homes, several commercial establishments, and three boatyard/marinas.

School Street Crossing has a roadway width of 25 feet. Sight distance in both directions, but especially to the east, is restricted by track curvature. The average daily traffic is approximately 900 vehicles. A pedestrian was killed by a train near this location in 1984, a vehicle/train accident at the School Street Crossing occurred in 1982 and involved an unoccupied stalled vehicle. A second vehicle/train accident occurred in 1994, which involved a low boy boat trailer. The boat trailer disconnected from the vehicle due to improper installation of safety pins as it traversed the crossing and was left on the rails of the crossing.

The "Amtrak Authorization Act of 1992" directed FRA to prepare a master plan for the New York to Boston portion of the NEC, and specifically requested that a special study be made of the steps needed to close all remaining highway at grade crossings in Connecticut, Rhode Island and Massachusetts. The "Draft Northeast Corridor Improvement Program - Plan for the Elimination of Highway At Grade Crossings", recommended the construction of an overpass at School Street Crossing in West Mystic. The final report, after opposition to the costly overpass was voiced at public information meetings, recommended that new technologies be explored. Among the most promising were four-gate systems used in some European countries, which provided maximum protection while permitting high-speed operations.

On January 28, 1993, the Connecticut Department of Transportation (CDOT) submitted a proposal to FRA under Sec. 1036 of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) to demonstrate advanced technologies to increase safety at grade crossings. The primary objective of the demonstration was to simultaneously enhance grade-crossing safety and permit speeds above 79 mph, the maximum allowed at non-grade separated crossing by FRA Safety Regulations. In April 1994, the Connecticut Department of Transportation received a grant from the National High-Speed Ground Transportation Technology Demonstration Program, FRA Grant Number DTFR53-94-600004. The total estimated cost of the demonstration project was \$1,000,000. FRA funding assistance was limited to 80 percent of the total cost, the State of Connecticut participated in 20 percent of the total project cost. The grant was amended in November 1996, to lengthen the time of performance.

On August 31, 1994, CDOT announced in a news release that America's first new high tech grade crossing protection system was to be put into operation. This system included a unique four quadrant gate installation design to prevent collisions between trains and vehicles, was to be built and tested at the Northeast Rail Corridor's School Street crossing in Groton (West Mystic).

Description of Operations

The advanced quad-gate crossing warning system with vehicle detection and exit gate indicator systems have a longer warning system, increasing vehicle dwell time from 30 seconds to 60 seconds.

Upon approach of a train the crossing warning system will be started at a point ahead of the crossing allowing sufficient time for the crossing cycle and for sufficient braking of the train to stop. Once the crossing warning system has started, the following will take place: The warning lights will flash, the bell will sound, and the entrance gates will begin to travel to a horizontal position. Once the entrance gates achieve the horizontal position a signal is sent to begin activation of the loop detector. After a predetermined amount of time, if the loop detectors do not detect a vehicle, a signal is sent to the exit gates. Once a signal is sent to the exit gates they will proceed to the horizontal position. When the exit gates are in a horizontal position, a signal is sent to the train through the rail circuits showing a clear cab signal. This information and operation of the gates and loop detectors has to be sent before a point that is set as the last and best stopping distance for a train to avoid hitting a vehicle at the intersection of the railroad and the highway. This point will be determined for the maximum allowed track speed. With a clear cab signal the train is free to proceed to authorized track speed across the crossing. As the train approaches a predetermined point before the crossing it is necessary to momentarily deactivate the loop detectors before the train passes over the protected area. This is necessary in order to avoid giving the train a restricting cab signal. After the train passes the protected area the loop detector is reactivated and checks the area, conceding the factor that there may be the possibility of rail traffic coming on another track. Once it is determined that all is clear in the protected area, the system will clear up in the following manner: The loop detector will deactivate, the exit gate will start up from the horizontal position to the vertical position, followed by the entrance lights and bell.

Example

There are many different scenarios to be considered for this crossing application. In this application there is a railroad bridge to consider and the possibility that the Mystic Station will play a role in the timing of the crossing activation.

One scenario, in order to demonstrate the operation of the crossing, maybe that the approaching train starts the cross warning system, (at a point which has been established to allow the sufficient time to elapse for the crossing to be closed and protected) the lights begin to flash, the bell sounds and the entrance gates begin to travel to the horizontal position. In this scenario, the driver of a vehicle approaching the activated crossing decides to travel around the entrance gate once they have reached the horizontal position. The presence of the vehicle as it passes over the loop detectors prevents the exit gates from receiving a signal from the loop detectors to begin their closure cycle. If the passage of the vehicle takes place after the exit gates have begun to cycle to a horizontal position, the clear indication to the exit gates is removed. Removal of this indication to the exit gates will cause the gates to reverse their downward movement and be driven back to the vertical position. After the exit gates are back to the vertical position the loop detectors will again assess the area and if a vehicle is not detected the signal to the exit gates to start their movement to a horizontal position will begin again. This scenario produces a restricting cab signal in the train engineer's cab, while the exit gates are not in the horizontal position. The train engineer must acknowledge this signal and make a brake application. Once the exit gates are determined to be in the horizontal position by the monitoring system a clear cab signal is transmitted to the train. The train may then proceed. The vehicle is assumed to have run around the gates, the train would receive a signal to stop short of the crossing, after the brake application, the train receives a clear signal. The engineer then would continue over the crossing barring any additional changes in the cab signal system. These hypothetical incidents would have other requirements imposed by the designated rail operating authority.

Management/Contractual Developments

CDOT originally attempted to contract with the firm of Asea Brown Boveri (ABB) Traction, Inc. Due to contractual issues concerning operations, design, materials and proposed technology the contract scope was never fully completed. In September 1997, CDOT with the encouragement of the FRA entered into a contract with Amtrak jointly developing and implementing the Conceptual Theory of Operation, System Design Concepts and it called for Operational Procedures. The final agreement went through more than a dozen revisions and over a year's worth of negotiations before it was signed. The scope of the agreement had three main sections:

Phase I Final Design System Engineering including: Site Details, Human Factors, System Engineering and Operational Analysis, Operational Scenarios, Human Fact Analysis, Environmental Factor Analysis, Maintainability Analysis, Design and Report, Performance and Design Specifications, and Design Concept.

Phase II Procure, Install and Verify Demonstration System Components including: System Design, Component Testing, Design Evaluation and Improvement, Reliability Testing, Maintainability Testing and Demonstration, Failure Analysis and Corrective Action, Design Review, Procurement, Installation and Testing the System.

Phase III Operational Demonstration and Evaluation including: Demonstration and Evaluation, Availability Assessment Reports; Protection Effectiveness, System Maintenance, Manuals and Training.

The Scope also included a schedule of deliverables, definitions, background, conceptual procedures of operation, warning and closure procedures, necessary approvals, permits (if required), utilities and general requirements and standards.

After FRA acceptance, July 18, 1998, was chosen as the final test date with all installation complete. The test was a complete success and Amtrak issued a Special Bulletin Order for all train crews and dispatchers announcing that the system was operational on July 20, 1998.

Separate from the FRA/CDOT grant, yet integral to the four quadrant gates system, was an agreement between the FRA, Amtrak and Union Switch and Signal (US&S) for US&S to provide a Micro-Lok Plus Microprocessor. This coordination of hardware and software incorporated crossing control logic of the warning system and the vehicle detection system, as well as monitoring systems that check crossing warning device status. It provided software programming for crossing control logic based upon Amtrak's requirements which included the automatic testing of vehicle detection system loops. It also provided logic for the downgrading of cab signals if any vehicle is detected on the crossing and a train is on the approach circuit. This agreement supplied the following:

- Twelve inch light emitting diode(LED) flasher units for all flashers involved in the project, as well as an extra set for emergency use.
- Two standard entrance gate mechanisms (model 95) complete with mast, signs and gate arms. Gate arms have standard incandescent lamps.
- Two Exit (that fail-safe in the up position) gate mechanisms (model 95) complete with mast, signs, and gate arms. Gate arms have standard incandescent lamps.
- One model 95 – gate mechanism for emergency use.
- Assistance to Amtrak for cutting over the Micro-Lok System, provide technical support involving Micro-Lok, LED flashers and model 95 mechanisms.
- Support and warranty of the installation for all US&S products for one year after in-service date.
- Local panel display, which indicates status of all components of system as required by Amtrak.
- A data logger recorder and program recorder for logging of all data as required by Amtrak.

Final Cost Summary

Amtrak (billed to CDOT)	\$731,040.00
CDOT Grant Administration Costs	\$ 67,175.00
Settlement of previous contract to ABB Traction, Inc.	<u>\$123,955.00</u>
Total	\$922,170.00

Acronyms

AADT	annual average daily traffic
ABB	Asea Brown Boveri, Ltd.
Action Plan	<i>Rail-Highway Crossing Safety Action Plan Support Proposals</i>
ADT	average daily traffic
CC	closed circuit
ConnDOT	Connecticut Department of Transportation
DOT	Department of Transportation
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
ISTEA	Intermodal Surface Transportation Efficiency Act
LACMTA	Los Angeles County Metropolitan Transportation Authority
LED	light emitting diode
LRT	light rail transit
MBTA	Massachusetts Bay Transportation Authority
NEC	Northeast Corridor
NECTP	Northeast Corridor Transportation Plan
NPRM	notice of proposed rulemaking
ODS	obstruction detection system
US&S	Union Switch and Signal

