Illinois High-Speed Rail Four-Quadrant Gate Reliability Assessment

U.S. Department of Transportation
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Safety of Highway Railroad Grade Crossings

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13. ABSTRACT (Maximum 200 words)
The Federal Railroad Administration (FRA) tasked the John A. Volpe National Transportation Systems Center (Volpe Center) to conduct a reliability analysis of the four-quadrant gate/vehicle detection equipment installed on the future high-speed rail (HSR) corridor between Chicago and St Louis. A total of 69 highway-rail grade crossings on a 120-mile (193 km) segment of the 280-mile corridor were equipped with four-quadrant gates and inductive loop vehicle detection technology. This segment, between Mazonia and Springfield Illinois, will eventually carry passenger trains at speeds up to 110 mph (177 km/h) at many of the highway-rail grade crossings.

The analysis was based on maintenance records obtained from the Union Pacific Railroad, the owner and operator of the highway-rail grade crossings. The results were used to assess the impact of the equipment reliability on the proposed HSR timetable. The Volpe Center study showed that the total average delay to the five scheduled daily high-speed passenger roundtrips was an estimated 10.5 minutes, or approximately 1 minute per train. Overall, extensive analysis of the trouble ticket data showed that the four-quadrant gate and vehicle detection equipment had a minimal direct impact on the frequency and duration of grade crossing malfunctions. Moreover, an overwhelming majority of crossing malfunctions equally impacted operations of both the entrance and exit gate equipment.

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LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

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1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
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1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

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LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

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1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

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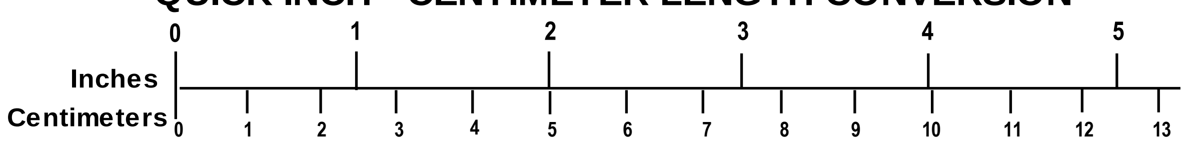
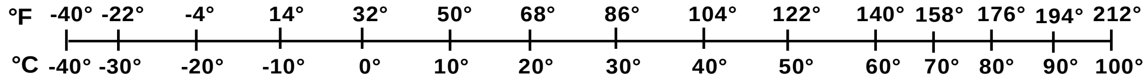


QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION



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Anya A. Carroll, Principal Investigator, Highway-Rail Grade Crossing Safety Research, the Volpe National Transportation Center, provided overall direction of the technical information and the report preparation, and also provided invaluable guidance and leadership.

Acronyms

AADT	average annual daily traffic
DI	Delay Index
EGM	Electronic Gate Monitor
EGMS	Exit Gate Management System
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
HSR	High-Speed Rail
IDOT	Illinois Department of Transportation
km/h	kilometers per hour
LRT	light rail transit
m	meters
MTTR	mean time to repair
MUTCD	Manual of Uniform Traffic Control Devices
MWRRI	Midwest Regional Rail Initiative
mph	miles per hour
NAJPTC	North American Joint Positive Train Control
NEC	Northeast Corridor
PTC	Positive Train Control
s	seconds
SEHSR	Southeast High Speed Rail
UPRR	Union Pacific Railroad
USDOT	U.S. Department of Transportation
Volpe Center	John A. Volpe National Transportation Systems Center

Table of Contents

Tables

Figures

Executive Summary

The implementation of high-speed rail (HSR) technology, at speeds of 80–110 miles per hour (mph), or 129–177 kilometers per hour (km/h), on corridors with pre-existing conventional rail service (up to 80 mph (129 km/h) poses several significant challenges, including extensive employment of at-grade highway-rail crossings. Frequently, these crossings cannot be closed or grade separated, and they are equipped with insufficient warning device technologies to support HSR operations. One solution was four-quadrant gates, with inductive loop vehicle detection, installed at 69 grade crossings on a 120-mile (193 km) segment of the future 280-mile (451 km) HSR corridor between the cities of Chicago and St Louis. This segment, between Mazonia and Springfield in the State of Illinois, will carry passenger trains at speeds up to 110 mph (177 km/h) at many of the highway-rail grade crossings. These and other infrastructure improvements were completed to reduce the Chicago to St. Louis travel time from 5 ½ to 3 ½ hours and increase the number of daily round-trips in each direction from three to five.

The U.S. Department of Transportation's (USDOT) Research & Innovative Technology Administration's John A. Volpe National Transportation Systems Center (Volpe Center), under the direction of the USDOT Federal Railroad Administration's (FRA) Office of Research and Development (R&D), conducted a reliability analysis of the four-quadrant gate/vehicle detection equipment based on maintenance records obtained from the Union Pacific Railroad, the owner and operator of the grade crossings. The results of this analysis were used to assess the impact of the equipment reliability on the proposed HSR timetable.

The Volpe Center study showed that the total average delay to the five scheduled daily high-speed passenger round-trips was an estimated 10.5 minutes or approximately 1 minute per train. Overall, extensive analysis of the trouble ticket data showed that the four-quadrant gate and vehicle detection equipment had a minimal direct impact on the frequency and duration of grade crossing malfunctions.

Analysis of trouble ticket data can be used to identify recurring maintenance issues that may require further study. This process may eventually lead to optimization of railroad inspection and maintenance procedures, which in the past, railroad inspection and maintenance procedures have been modified to minimize the frequency and impact of malfunction events. Fortunately, longitudinal analysis of maintenance data will facilitate identification of such long-term trends. On the basis of this research, railroad and state engineers will be able to review and, if necessary, modify maintenance procedures to optimize operation of the four-quadrant gate technology.

1. Introduction

The Intermodal Surface Transportation Efficiency Act of 1991 designated five future high-speed rail (HSR) corridors (Federal Railroad Administration (FRA), 1997):

- Pacific Northwest
- California
- Chicago Hub Network
- Florida
- Southeast

The Chicago HSR corridor established a “hub-and-spoke” system centered on Chicago, IL, with termination points in St. Louis, MO, Detroit, MI, and Milwaukee, WI (FRA, 1997). This effort, part of the broader Midwest Regional Rail Initiative (MWRRI), will eventually interconnect nine states over a 3,000-mile (4,631 km) system shown in Figure 1. The overall goal of the MWRRI is to achieve reliable and frequent HSR service with trains operating at speeds between 90–110 mph (145–177 km/h). The features of this service will include new train sets, track infrastructure improvements, four-quadrant gate warning device technology at high-speed highway-rail grade crossings, and railroad signals accommodating the increased speed regimens (Transportation Economics and Management Systems, Inc. et al., 2004).

Figure 1. Midwest High-Speed Rail Network (Transportation Economics and Management Systems, Inc., and HNTB Corp., 2004)

These HSR systems are being implemented on pre-existing rail corridors, with highway-rail grade crossings that usually cannot be closed or separated. Typically, these crossings are not equipped with the risk mitigation technologies recommended by the United States Department of Transportation (USDOT) Federal Railroad Administration (FRA) for rail operations in the 80-110 mph (145–177 km/h) speed regime (FRA, 1994a). These recommendations, although not required, include the installation of sophisticated traffic control/warning devices such as four-quadrant gates equipped with constant warning time and vehicle detection equipment.

1.1 North American Joint Positive Train Control Program

The North American Joint Positive Train Control (NAJPTC) program was created in 1998 under the sponsorship of the FRA in a public-private partnership with the Association of American Railroads and the Illinois Department of Transportation (IDOT) (FRA, 2008). The ultimate goal of this program was a reduction of the Chicago–St. Louis train timetable from 5 ½ to 3 ½ hours. In 2000, IDOT selected the 120-mile (193 km) segment between Springfield and Mazonia as a test bed for the program, incorporating 110 mph (177 km/h) passenger train service and employing radio-based positive train control (PTC) technology. The complete objectives of the program are listed in Table 1 and the system functionality is shown in Table 2.

NAJPTC train control technology proved to be very complex and required substantial further development before being ready for revenue service operations. In January 2007, the program was transferred to a train control test bed at the Transportation Technology Center in Pueblo, Colorado. IDOT then elected to install a traditional cab-signal system that will provide the safety-critical functionality necessary for safe 110-mph (177 km/h) HSR operations. Once the Springfield–Mazonia segment is operational, IDOT expects to upgrade the 30 mile (48 km) Joliet–Dwight and the 90 mile (145 km) Springfield–Granite City segments in a similar fashion, thereby further reducing the Chicago-St. Louis trip time further (FRA, 2008; Midwest High Speed Rail Association, n.d.).

Table 1. NAJPTC Program Objectives (Polivka, 2005)

Objective	Description
Safety	Demonstrate PTC safety functionality • Prevent train-to-train collisions • Enforce speed restrictions • Protect roadway workers operating under specific authorities
Interoperability	Develop interoperability standards • Nonproprietary design • Railroads own the design (including source code)
Cost	Produce cost-effective design with maximum use of commercial-off-the-shelf components
Mixed mode operation	Develop revenue-ready system for high speed passenger trains intermixed with freight trains

Table 2. NAJPTC System Functionality (Polivka, 2005)

- Warnings/enforcement of authorities and speeds
- Modular design–for tailored or evolutionary deployment
- Locomotive activation of highway crossing warning systems
- Eliminates need to extend crossing track circuits for high-speed operation
- Fail-safe (vital) implementation and moving block
- Potential to reduce delay during overtakes and recovery from
- disruptions
- Potential to increase capacity without adding track
- Potential to alleviate need for wayside signals
- Enables high-speed (passenger) train operation
- Open, nonproprietary design–for interoperability & lower recurring cost
- Remote control of switches from locomotive
- Boundary protection
- Handling of equipped and unequipped trains on same track
- Detection, reporting, and protection against rogues & emergencies
- Remote monitoring of train locations and movements
- Potential for paperless bulletins and authorities

1.2 Purpose

Although installed on a limited basis, grade crossings equipped with four-quadrant gates and inductive loop vehicle detection have proven to be an excellent solution in situations where grade separation or closure are precluded. The typical application for this crossing treatment, especially on HSR corridors, involves about one-half dozen crossings separated by several miles of right-of-way.

The NAJPTC system, with 69 four-quadrant gate crossings in a span of 120 miles (193 km), is the first large-scale deployment of this treatment type. FRA tasked the USDOT Research & Innovative Technology Administration's John A. Volpe National Transportation Systems Center (Volpe Center), to evaluate the reliability of the grade crossing equipment and the potential impact, if any, on the proposed HSR timetable.

1.3 U.S. Four-Quadrant Gate Experiences

Although four-quadrant gate technology has been extremely successful as a grade crossing safety treatment, HSR experience in the United States has so far been limited to the Northeast Corridor (NEC) in Connecticut and the Southeast High Speed Rail (SEHSR) corridor in North Carolina. The benefits of the use of this treatment at crossings on these corridors, which demonstrate the operational range of four-quadrant gate technology, have been well documented (FRA, 2007; FRA, 2001). In addition, the Los Angeles County Metropolitan Transit Authority has aggressively deployed four-quadrant gate technology through its light rail transit (LRT) system.

Through June 2008, a total of 24 crossings have been installed on the Los Angeles Blue and Gold LRT lines (A. Zohbi, personal communication, June 2, 2008).

The original NEC HSR improvement strategy was to either close or separate all remaining public grade crossings on the corridor (FRA, 1994b). However, neither solution was feasible at eight grade crossings in Connecticut for two particular reasons: environmental implications of grade separation and the potential disruption to local communities resulting from crossing closure. This situation precipitated the deployment of four-quadrant gate technology currently in revenue service. In this configuration, an inductive loop vehicle detection platform is vitally integrated with the track circuit based cab signaling system. This system is activated by conventional track circuits and secures the crossing to prevent motor vehicles from entering during a train event. The grade crossing signaling and control system is interconnected with the wayside and in-cab signaling systems of Amtrak, the NEC HSR service provider. Any compromise in the integrity of the grade crossing equipment is communicated to the locomotive engineer by means of the cab signaling system and results in a speed restriction of as low as 15 mph. A motor vehicle occupying the crossing, even temporarily, will produce a speed restriction in the vicinity of the crossing and cause the exit gates to ascend (FRA, 2001).

The “Sealed Corridor” initiative is a three-phase analysis of the SEHSR corridor between Charlotte and Raleigh, NC. This corridor consists of 216 grade crossings, 44 of which are private. The crossing treatments include median barriers, long gate arms, four-quadrant gates, and closing of redundant crossings. Other elements of the initiative include traffic separation studies to consolidate crossings, video enforcement, video monitoring, data collection, studies of driver behavior and the demographics of violators, innovative warning devices, and use of improved signs at private crossings.

The Phase I Sealed Corridor Report to Congress (FRA, 2001) examined 100 at-grade crossings, of which 52 were either improved or closed, including 13 treated with four-quadrant gates. Unlike the Amtrak system in Connecticut, the North Carolina four-quadrant gate warning devices do not employ vehicle detection. The exit gate operation is timed, with an exit gate delay in the range of 4–10 seconds (s), to allow motor vehicles to clear the crossing before train arrival (Norfolk Southern Corporation and North Carolina Department of Transportation, 2000). Through 2007, 49 four-quadrant gate crossings have been installed on the SEHSR, though without vehicle detection functionality.

1.4 Report Layout

Section 2 of this report provides an overview of the Illinois HSR corridor and a technical explanation of the four-quadrant gate and vehicle detection systems. Section 3 presents a description of the research methodology and an analysis of the reliability data and Section 4 presents the results of the data analysis and a subsequent discussion.

2 Illinois HSR Corridor

Figure 2 shows the HSR corridor between Chicago and St. Louis. The corridor is owned and operated by the Union Pacific Railroad (UPRR), and contains a mix of freight, intercity conventional passenger rail, and commuter rail service. The majority of the line is single track and at the time the HSR program was initiated, Amtrak operated three daily round-trip passenger trains. In 2006, the frequency was increased to five daily round-trip trains.

The initial goal for the HSR service was eight round trips per day between Chicago and St. Louis, with one-way end-to-end travel time of approximately 3 ½–4 hours. However, lower than expected funding precluded any further infrastructure improvements between Chicago and Dwight, Illinois. Furthermore, fewer high-speed train sets than originally anticipated are being procured. As a result, the level of service is now projected at three round-trips per day, with a one-way trip time of 4-4 ½ hours.

The yellow highlighted portion in Figure 2, between Springfield and Mazonia, has undergone extensive track rehabilitation, including construction of 12 miles (19 km) of double track and 22 miles (35 km) of freight sidings, and now satisfies FRA Class 6 track regulations for 110 mph (177 km/h) train service.

Figure 2. Illinois HSR Corridor (Tse, 2005)

During the initial environmental impact assessment process, 322 public and private crossings were identified on the corridor of which 11 have since been closed, leaving 311 remaining. In the draft environmental impact statement (DEIS), 68 vehicle and 17 pedestrian crossings were proposed for closure. However, opposition from many impacted communities limited the number of closures proposed in the final environmental impact statement (FEIS) to 10 vehicle and 14 pedestrian crossings. As a result, 174 grade crossings were scheduled to be equipped with upgraded warning devices. This consisted of 118 crossings with four-quadrant gates and vehicle detection as required by Illinois Commerce Commission regulations for train speeds in excess of 79 mph (127 km/h), 51 dual-gate crossings, 4 pedestrian crossings with bells and flashers, and one locked gate at a private crossing . Ultimately, the total number of four-quadrant gate crossings was reduced to the 69 grade crossings between Springfield and Mazonia, including 49 that support HSR operations highlighted in red in Appendix A (Federal Highway Administration (FHWA), FRA, and IDOT, 2003).

Of the 69 four-quadrant gate crossings, 62 were classified as rural and seven were classified as urban. As depicted in Figure 3, average annual daily traffic (AADT) at more than two-thirds of the crossings is less than 1,000. [1] This type of low-motor vehicle traffic environment lends itself particularly well to the implementation of four-quadrant gate crossing operations at speeds between 90 and 110 mph (145–177 km/h).

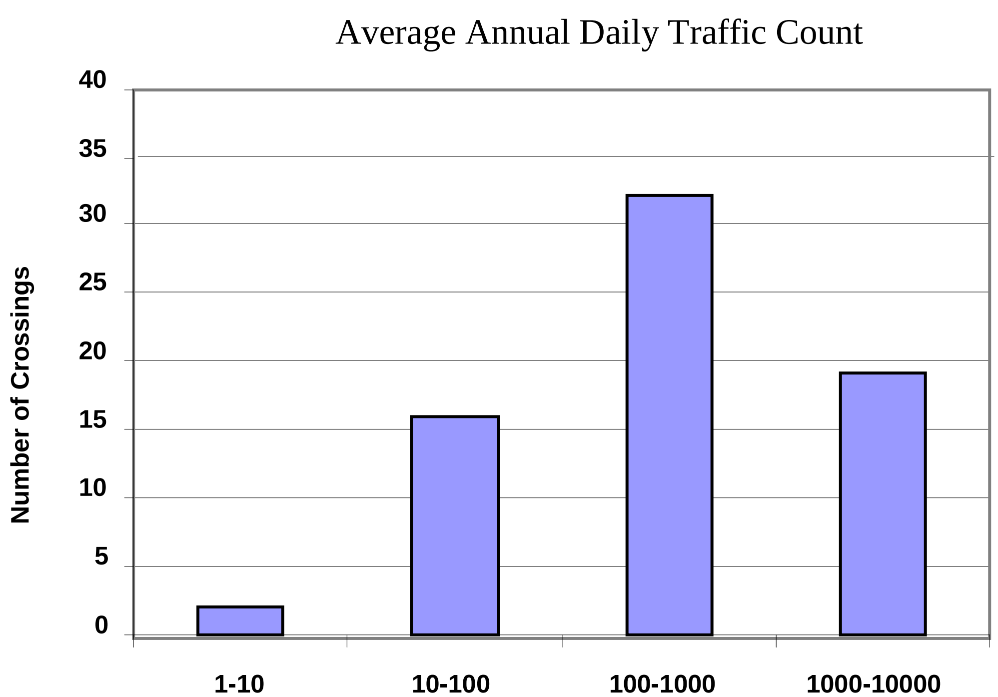


Figure 3. AADT Distribution of the 69 Four-Quadrant Gate Crossings

[1] FRA Office of Safety Analysis database (safetydata.fra.dot.gov)

2.1 Four-Quadrant Gate Design

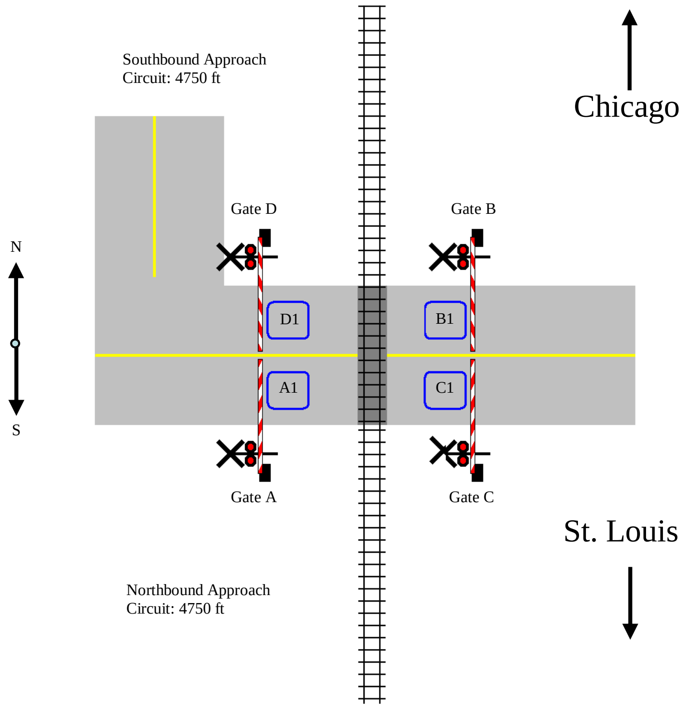
Of the 69 four-quadrant systems installed, 12 were manufactured by Union Switch and Signal and 57 by Western Cullen Hayes. The grade crossing equipment is continually monitored for faults by a solid-state controller. These faults include: crashing of entrance gate arms resulting from a sudden power loss, pumping of gate arms, crashing of counterweights if a gate arm becomes detached, and overloading of motors caused by a stuck gate arm.

The four-quadrant gate crossing system is comprised of the exit gate management system (EGMS), the vehicle detection subsystem, and the gates. The EGMS, manufactured by Railroad Controls Limited, is a microprocessor-based controller that works in tandem with the vehicle detection system to resolve motor vehicle presence within the grade crossing and supply the appropriate gate response. During a train event at the crossing, the EGMS prevents the exit gates from lowering until motor vehicle traffic is no longer detected in the crossing (Railroad Controls Limited, 2004). If the EGMS detects a compromise in the health of the vehicle detection equipment, it instructs the exit gates to ascend.

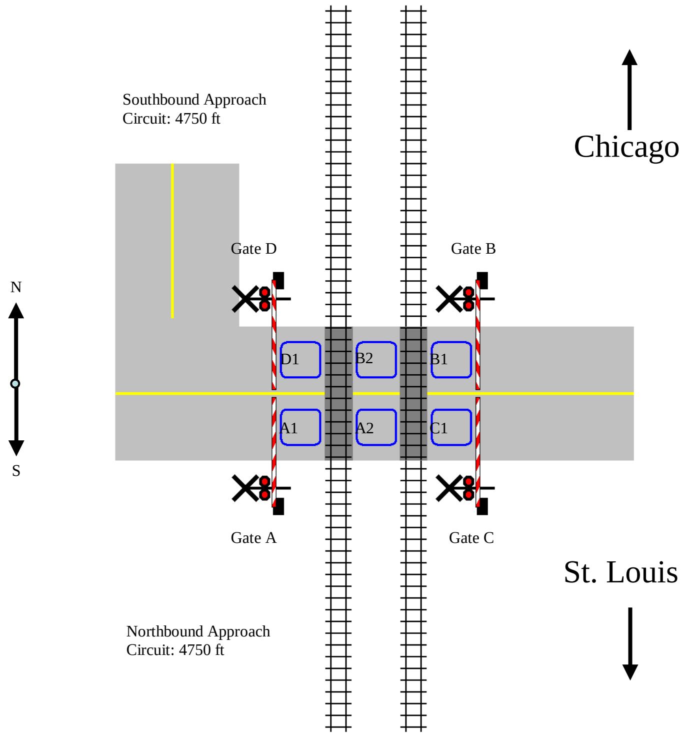
The four-quadrant gate equipment was designed for compliance with the Manual of Uniform Traffic Control Devices (MUTCD) (MUTCD Chapter 8D, 2003). Each gate arm is fully reflectorized on both sides with red and white stripes and equipped with three red flashing lights. At grade crossings with two-way highway traffic, back-to-back flashing light signals are installed on each side of the tracks in all four quadrants. On multilane, one-way streets and divided highways, flashing lights are installed on both sides of the road at the entrance to the crossing. When the gates are closed, each gate is required to extend across the entrance and exit gate lanes of road traffic.

The vehicle detection subsystem was designed in accordance with Part 3.1.15 of the American Railway Engineering and Maintenance-of-Way Association Communications and Signaling Manual, *Recommended Functional/Operating Guidelines for Control of Automatic Highway-Rail Grade Crossing Warning Systems* (Milewski, 2005). Each inductive loop consists of a prefabricated shared conduit with a single-turn check loop that runs the entire perimeter of the three-turn primary loop. The detector amplifier periodically shorts the check loop, resulting in a change in inductance, thereby simulating detection of a motor vehicle. If the inductance change is not equal to a predefined reference value, the detector displays a message indicating failure of the loop. Under this scenario, either the EGMS will direct the exit gates to ascend or the crossing will revert to timed operation mode (Reno A and E, undated).

The vehicle detection technology consists of inductive loops embedded within the roadway, connected to a solid state vehicle detection unit on the wayside. At single track locations, four loops are installed in each approach and exit highway quadrant inside the grade crossing gates. For double-track grade crossing applications, an extra pair of loops is installed between the tracks. These configurations are illustrated in Figure 4. As described previously, this technology has been successfully implemented on Amtrak's NEC HSR corridor in Connecticut. However, the Illinois configuration is not integrated with the train control system.



a) Single track configuration



b) Double track configuration

Figure 4. Four-quadrant Gate (a) Single Track and (b) Double Track Configurations

2.2 Illinois System Operational Overview

The EGMS operates in two modes with respect to exit gate operation; "dynamic" and "timed." In dynamic mode, which is the primary operational state, exit gate function is dependent on the presence and detection of vehicles within the grade crossing. If no vehicles are detected, the entrance and exit gates descend simultaneously. Timed mode is the EGMS backup operational state. If failure occurs in the EGMS hardware or the vehicle detection subsystem, exit gate descent is delayed until the entrance gates have reached the horizontal position. This operational mode provides an exit means for vehicles within the crossing when the warning system is activated.

The system is designed for fail-safe operation, meaning that the equipment will fail in the most restrictive operational state, so as to minimize the increase in risk. Thus, in either dynamic or timed operational mode, a loss of system power will result in the entrance gates descending and the exit gates ascending. Like the previous description of timed mode, this condition provides a path for vehicles within the crossing to exit if power fails. Because the entrance gates remain lowered, the railroad civil speed limit at the crossing is reduced to 15 mph (24 km/h).

The basis for the high-speed capability of the four-quadrant gate crossings is the advanced activation function in which an approaching PTC-equipped train interrogates the health status of the grade crossing using a radio-based communication link. This function is an overlay to the underlying conventional track circuit crossing activation circuitry. However, advanced activation provides vital support to high-speed operations at the four-quadrant gate crossings in two key respects; 1) a constant warning time for train time to arrival and 2) a safe distance for responding to speed restrictions if the crossing health status is compromised.

Each PTC-equipped locomotive contains an onboard computer with a database of equipped crossings, including location, track circuit configuration, conventional approach speeds, and warning times. As the locomotive approaches a grade crossing, the locomotive computer initiates an advanced activation session with the PTC equipment at the grade crossing. Once the advanced activation session is established, the locomotive computer transmits the estimated train arrival time to the crossing based on its predicted speed, current locomotive control settings, and train and track characteristics. The grade crossing equipment processes the information and transmits a response to the locomotive that includes the operational status of the advanced activation function and the total time the crossing has been activated (ARINC and CANAC, 2000). If the crossing equipment is either inoperative or the equipment status cannot be established, the PTC system will generate a speed restriction equal to the track circuit configuration of the crossing, typically 79 mph (127 km/h) (Weber, G., personal communication, May 29, 2007).[2]

2.3 Vehicle Detection System Operational Sequence

The four-quadrant gate crossings are designed for a 30-second minimum warning time for passenger and freight trains operating at 79 mph (127 km/h) and 60 mph (97 km/h), respectively.

[2] Although the PTC technology is being replaced by a conventional cab-signal system, IDOT anticipates that the advanced activation functionality will be integrated within the cab-signal system.

When a grade crossing is activated, the gate warning lights flash for 5 seconds. In dynamic mode operation, if no motor vehicles are detected and the crossing equipment is operating normally, both the entrance and exit gates will descend in tandem. All four gates will arrive at the horizontal position within 10 seconds of beginning descent and remain there for a minimum of 15 seconds before train arrival. This sequence is depicted in Figure 5. During this time, if a vehicle is detected within the crossing, the exit gates will cease lowering and begin to ascend. Once the detection system verifies the crossing is unoccupied, the exit gates will resume descending. When all of the gates reach the horizontal position and the grade crossing island circuit is activated by a train, the vehicle detection system is inhibited. This prevents the train from being incorrectly detected as a highway vehicle, which would result in the inadvertent raising of the exit gates by the EGMS. Once the rear end of the train clears the island circuit, the gates begin to ascend and return to the vertical position within 12 seconds.

Any malfunction of the EGMS, crossing gates, or the vehicle detection system, will result in the four-quadrant gate system automatically defaulting to timed mode operation. In this scenario, the exit gates do not initiate descent until the entrance gates are in the horizontal position, thereby allowing motor vehicles to clear the crossing. Additionally, all the gates are required to be in the horizontal position a minimum of 5 seconds before the arrival of a train at the crossing.

Under certain conditions, speed restrictions are issued to the locomotive as it approaches a four-quadrant gate grade crossing. The first case involves either a non-PTC-equipped locomotive or faulty advanced activation functionality at a crossing. In response, the PTC system will revert to the underlying track circuit signaling system and the corresponding maximum track speeds. On the IDOT HSR corridor, these speeds are typically 79 mph (127 km/h) and 60 mph (97 km/h) for passenger and freight operations, respectively. The second scenario is a consequence of the crossing equipment being activated more than 2 minutes. If the activation time falls between 2 and 5 minutes, the existing track circuit speed limit is enforced. In situations involving the equipment being activated greater than 5 minutes, a locomotive speed restriction of 15 mph (24 km/h) is generated.

When a crossing alarm is activated, a trouble ticket is automatically issued and a maintainer is dispatched to the crossing. Once the issue is resolved, the maintainer updates and closes out the trouble ticket. These records are stored electronically by the UPRR at its central office in Omaha, Nebraska. A sample trouble ticket is shown in Appendix B.

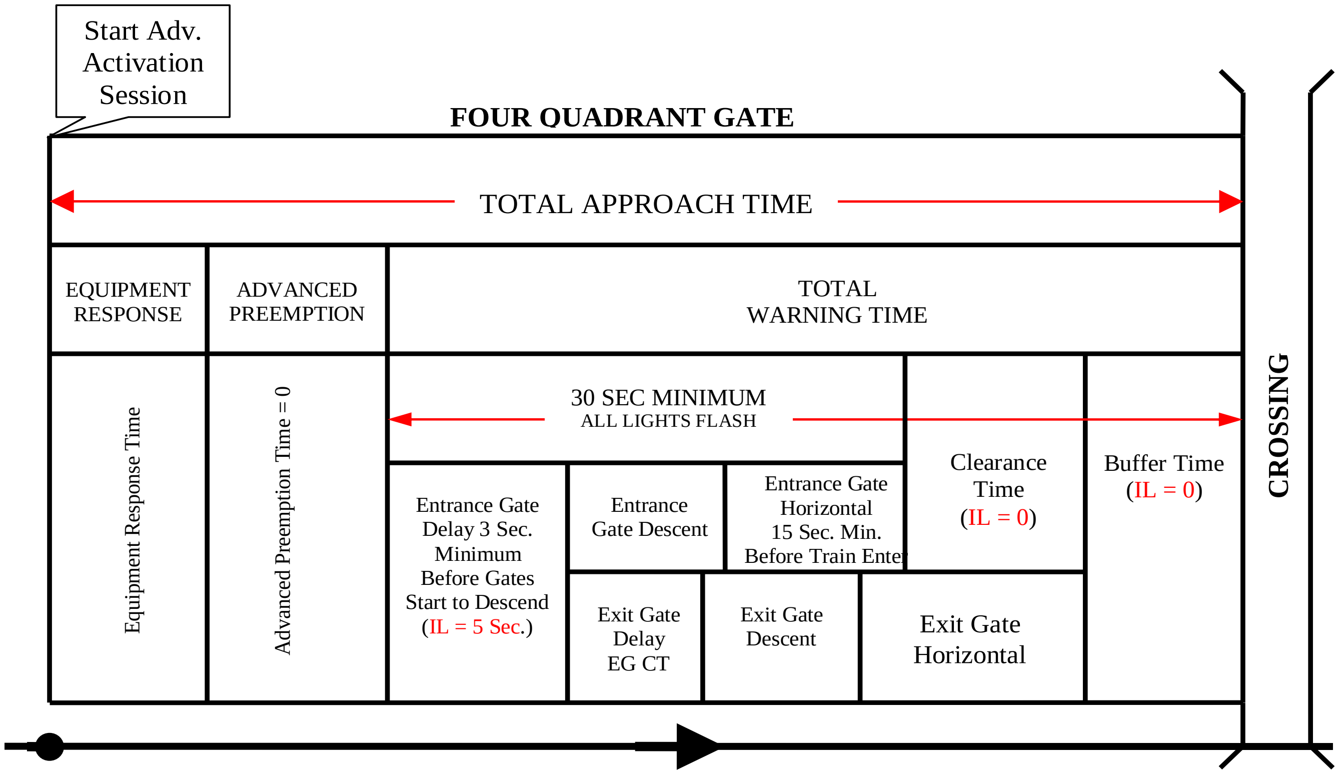


Figure 5. Four-quadrant Gate Crossing System Timing

3 Research Methodology

The evaluation process consisted of 1) identifying and characterizing the malfunction types, 2) calculating the probability of occurrence and mean time to repair (MTTR) for each malfunction type, and 3) estimating the resulting cumulative delay on the proposed HSR timetable.

In April 2005, FRA sent a formal request to UPRR requesting trouble ticket reports for four-quadrant gate vehicle detection technology installed on the Illinois HSR corridor (see Appendix C). In May 2005, the UPRR forwarded trouble tickets pertaining to the exit gates, EGMS, and the vehicle traffic detection loops for the period from May 9, 2003, and May 3, 2005, (Breeden, personal communication, May 13, 2005). In November 2005, the Volpe Center made a second request to UPRR for trouble ticket reports relevant to both entrance and exit gate maintenance calls. UPRR satisfied this request in February 2006 by providing trouble ticket reports from January 2004 through December 2005 (Breeden, personal communication, February 23, 2006). These two sets were evaluated by the Volpe Center for trends in malfunction occurrences and maintenance downtimes that may impact the future HSR timetable. The second set was employed as part of a “before and after” case of the original dual-gate technology on the HSR corridor with the four-quadrant gate and vehicle detection systems. Both datasets were used to characterize the impact from grade crossing equipment malfunction on the future HSR timetable from the types and frequencies of grade crossing equipment malfunctions.

3.1 Evaluation Assumptions

- A constant train velocity of 110 mph (177 km/h) was assumed for the entire corridor.
- The anticipated number of daily round-trip HSR trains ranges from 6 to 16, depending on the available level of funding support for the service.
- The high-speed alternative, the most ambitious approach, has a one-way trip travel time of 3.5 hours and a 110 mph (177 km/h) maximum train velocity on most of the corridor with 125 mph (202 km/h) on an 18-mile (29 km) stretch between Lincoln and Springfield, Illinois. The preferred alternative has a one-way trip travel time of 4 to 4.5 hours, subject to the extent of the infrastructure upgrades. The maximum train velocity under this option is 79 mph (127 km/h) between Chicago and Dwight and 110 mph (177 km/h) between Dwight and St. Louis.

The values employed in this analysis, 10 round-trip trains per day and a one-way travel time of 3 hours and 50 minutes, fall between these two estimates. The high-speed timetable shown in Table 3 reflects these assumptions.

Table 3. Typical Representation of the Chicago-St. Louis High-Speed Rail Timetable

Mile	Southbound: Read Down						Northbound: Read Up				
0	6:45a	8:15a	3:20a	5:15p	7:15p	Chicago	8:25a	10:25a	12:20a	7:00p	9:00p
12						Summit					
37						Joliet					
74						Dwight					
92						Pontiac					
124						Normal					
156						Lincoln					
185						Springfield					
224						Carlinville					
257						Alton					
284	10:35a	12:05p	7:10p	9:05p	11:05p	St. Louis	4:35a	6:35a	8:30a	3:10p	5:10p

3.2 Analysis of Entrance and Exit Gate Data

Data Set I refers to the 93 trouble ticket records for the time period from May 9, 2003, to 2005. This data set, collected over 726 days, reflects 14 different malfunction types, as by the Pareto distribution in

Figure 6. Analysis of the data showed that four malfunction types contributed to 75 percent of the total number of trouble tickets, and the remaining 10 types were responsible for the other 25 percent.

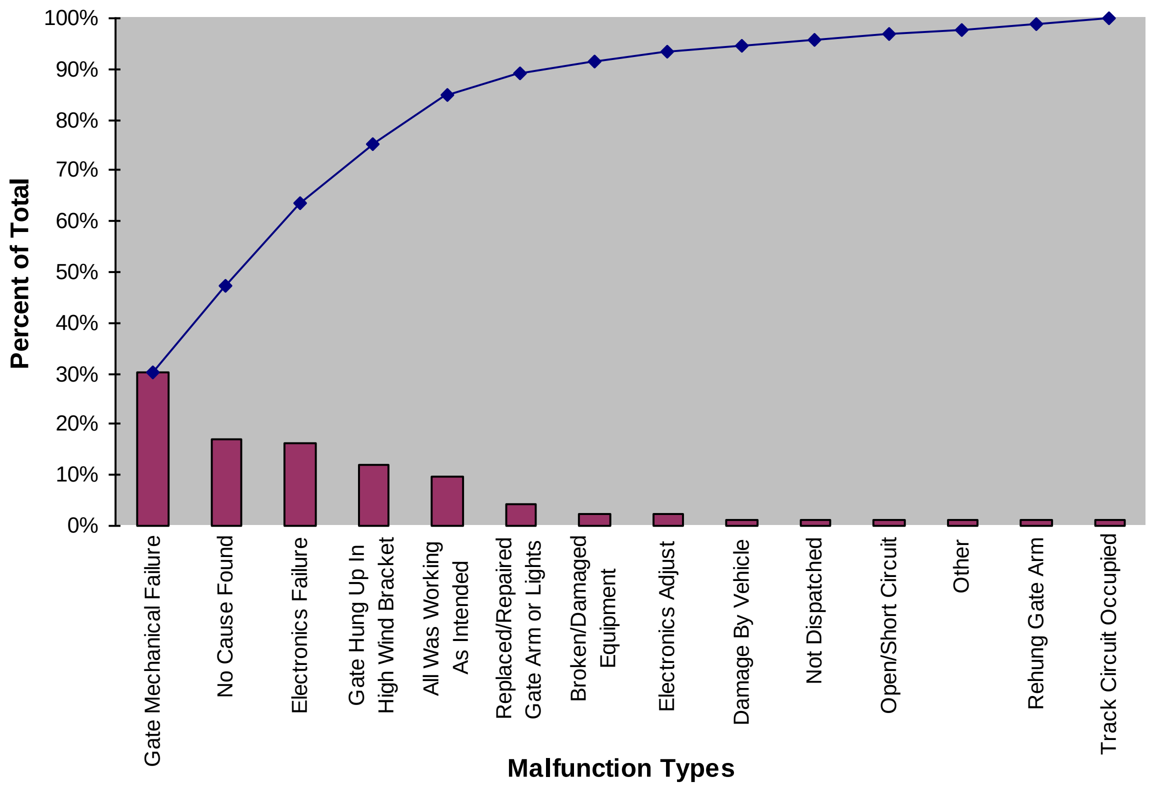


Figure 6. Pareto Distribution of Malfunctions from Data Set I by Reported Cause

The 14 malfunction types were reclassified into the nine categories related to grade crossing equipment reliability shown in Table 4. As shown in the Figure 7 pie chart, four malfunction types, totaling 28 percent of the trouble tickets—EGMS, loop detector, loop sensor, and exit gate activation—were specific to exit gate equipment. Exit gate activation issues, mostly arising from oversensitive loop sensors and detectors, accounted for 22 percent of the trouble ticket reports. This condition was typically resolved by decreasing detector sensitivity, but maintaining it above the motor vehicle detection threshold.

Table 4. Exit Gate Malfunction Type Definitions

Category	Definition
Electronic gate monitor (EGM)	Malfunctions in this group require the EGM to be reset.
Exit gate activation	This is potentially related to the loop detection system sensitivity being set too high, usually in conjunction with some form of external electrical noise. In the event of this type of malfunction, a loop may indicate vehicle detection when no vehicle is present.
Exit gate management system	A failure of the EGMS hardware or firmware is resolved by either resetting or replacing the EGMS controller board.
Gate mechanical	This type of malfunction results from dirty gate cams not making full up or down contact, thereby causing entrance or exit gates to not report horizontal or vertical position properly. Replacing or repairing the mechanical parts that control gate movement usually resolves this issue.
Loop detector	The loop detector is installed inside the EGMS rack and monitors the status of the inductive loops. A failure in the loop detector is indicated by an EGMS alarm. This is resolved by either resetting or replacing the loop detector controller board.
Loop sensor	If the self-check function detects an inductive loop component failure, a loop detector alarm is activated and the exit gate operation defaults to timed mode.
Nonspecific	Although malfunction causes were observed, they could not be assigned to a specific category type.
Wind	Usually indicative of gates hung up on the high wind brackets or gates pumping up and down from high wind. Normally, repositioning the exit gates and adjusting the gate contacts resolve this issue.
Wiring	This is manifested by a loose or broken wire in the crossing/vehicle detection electronics or the electromechanical equipment controlling gate movement.

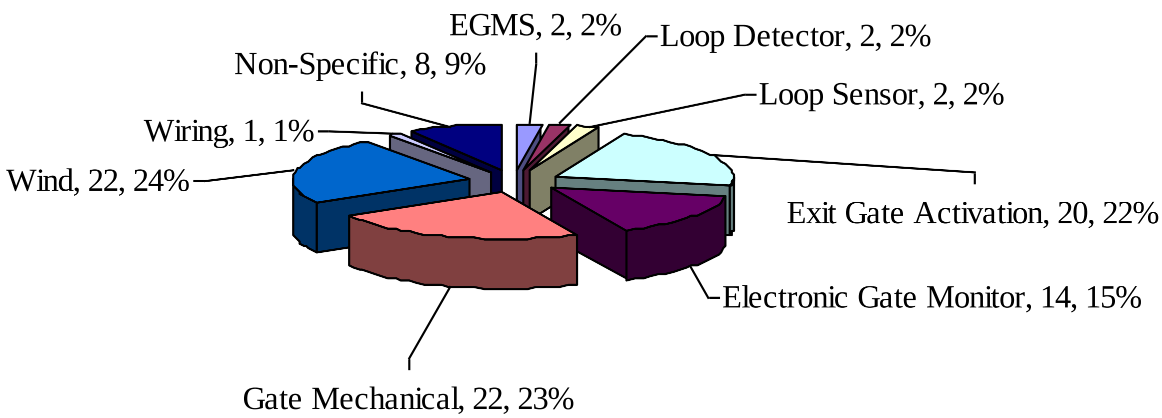


Figure 7. Exit Gate Trouble Ticket Distribution from Data Set I

Data Set II entrance and exit gate malfunction data were used to analyze the impact of the four-quadrant gate/vehicle detection system on the HSR corridor timetable. The data collection period spanned 677 days between February 2004 and December 2005. In total, 889 unique trouble tickets were tabulated, equating to an average of 1.31 malfunctions per day. Altogether, 37 different malfunction types were identified as being specific to the grade crossing equipment. Analysis of the data showed that seven malfunction types, as depicted by the Pareto distribution in

Figure 8, contributed to 80 percent of the total number of trouble tickets. The other 30 types accounted for the remaining 20 percent.

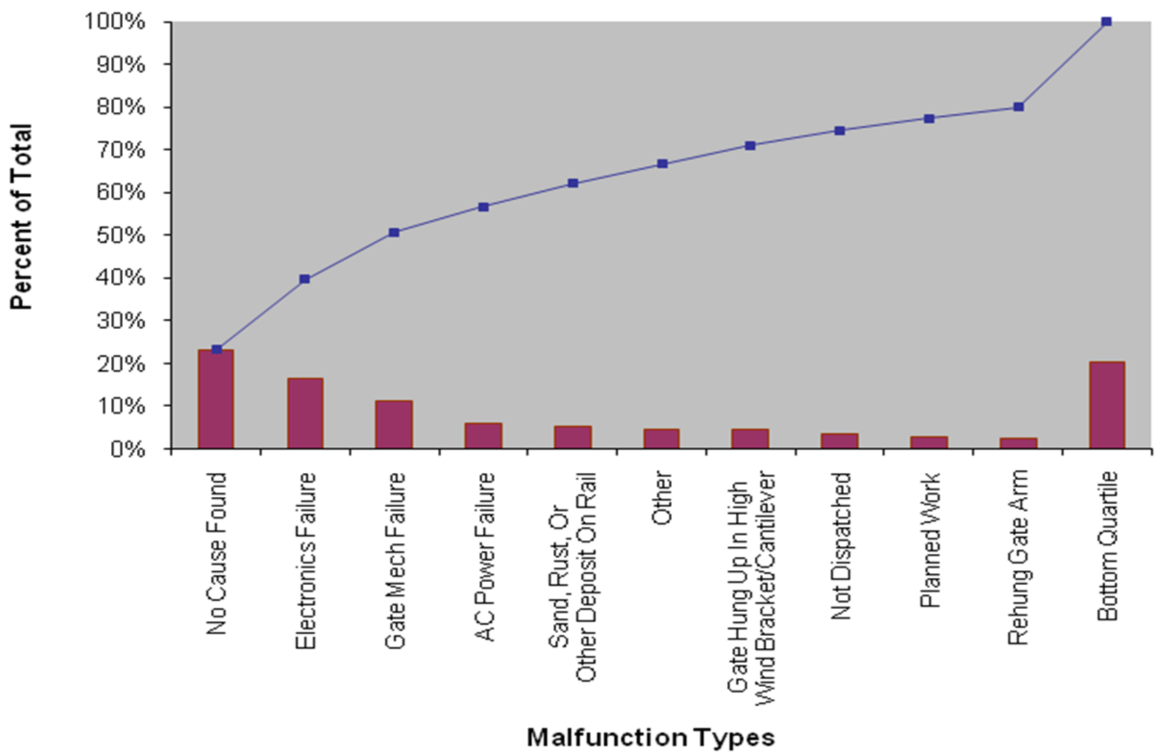


Figure 8. Pareto Distribution of Malfunctions from Data Set II by Reported Cause.

The weighted probabilities of occurrence and MTTR for each malfunction type were used to calculate the impact of the four-quadrant gate/vehicle detection system on the proposed HSR timetable. Further analysis of the MTTR data revealed a significant time-based component with several orders of magnitude between the highest and lowest values. This is more typical of a log-normal distribution rather than a normally distributed, symmetric distribution. For this type of application, the geometric mean, which is related to the log-normal distribution, provides a more realistic depiction for averaging data.

3.3 Theoretical Analysis of Average Time to Fix

For normally distributed, symmetric data, the arithmetic mean would typically be used. However, analysis of the MTTR data revealed a significant time-based component with several orders of magnitude between the highest and lowest values. Also, the data sets are positively skewed and bounded by zero. These characteristics are associated with a log-normal distribution rather than a normally distributed, symmetric distribution.

For this type of application, the geometric mean, which is related to the log-normal distribution, provides a more realistic average time to fix estimate. Figure 9 shows an example of a log-normal distribution compared to a normal distribution how the data distributions for the *No Cause Found* type responded to the geometric mean.

3.4 Theoretical Analysis

Consider a set of positive data containing n elements, $[a_1, a_2, \ldots, a_n]$. The geometric mean of this set is defined as the nth root of the product of all the elements. This is expressed as

$$\left(\prod_{i=1}^{n} a_i\right)^{1/n} = \sqrt[n]{a_1 \cdot a_2 \cdot \ldots \cdot a_n} \quad (1)$$

This value is less than or equal to the arithmetic mean of the data set and, the two means are equal if and only if all data elements are identical.

By using the logarithmic identity, $a^n = \left(e^{\ln a}\right)^n$, the formula may be written as

$$\left(\prod_{i=1}^{n} a_i\right)^{1/n} = \exp\left[\frac{1}{n}\sum_{i=}^{n} \ln a_i\right] \quad \text{(2), where}$$

$$\exp\left[\frac{1}{n}\sum_{i=}^{n} \ln a_i\right] = e^{1/n\cdot((\ln(a_1)+(\ln(a_2)+\ldots(\ln(a_i))}$$

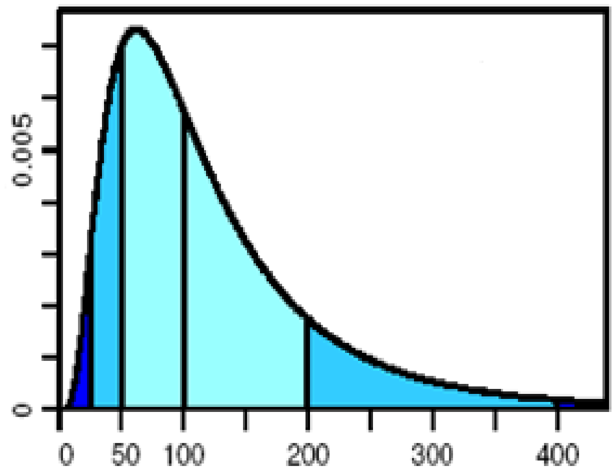
Since $\ln x + \ln y = \ln(x \cdot y)$, equation (2) can be rewritten as

$$\exp\left[\frac{1}{n}\cdot \ln\left(\prod_{i=1}^{n} a_i\right)\right] \quad (3),$$

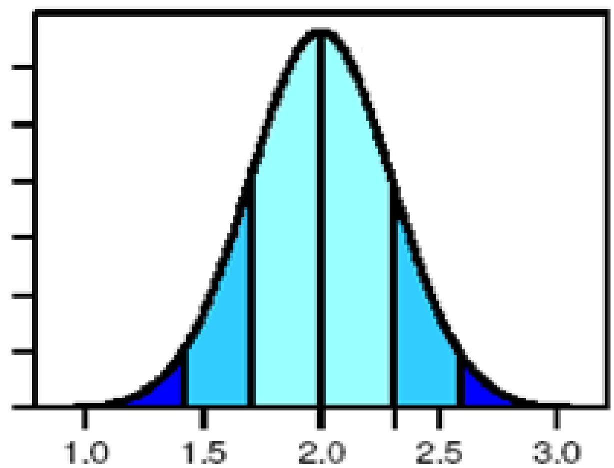
and can be reduced to

$$\left(\prod_{i=1}^{n} a_i\right)^{1/n} \quad (4)$$

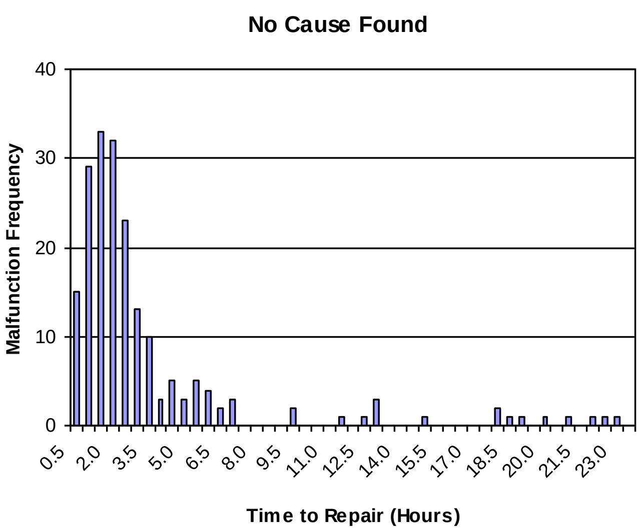
This is the exponentiated arithmetic mean of the logarithm transformed values of a_i or the geometric mean (Mian, 2002). Here a_i is the set of repair time values for a single failure type.



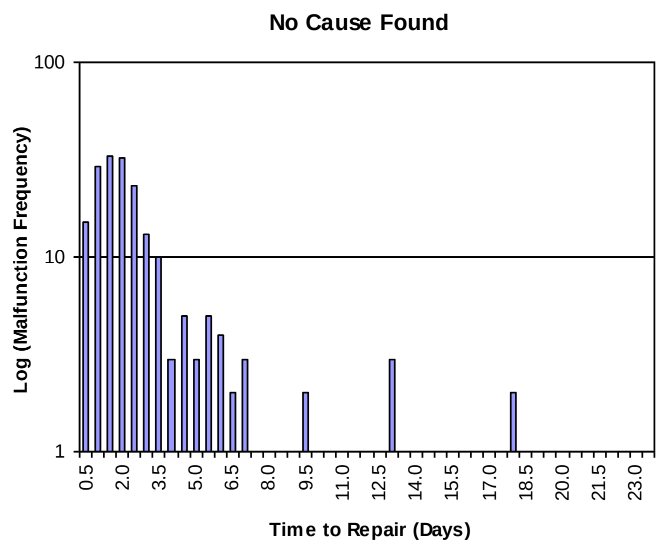
a) An example of an-adjusted log-normal distribution.



b) An example of a log-normal distribution on log-normal scale.



c) Unadjusted No Cause Found malfunction frequency distribution.



d) No Cause Found malfunction frequency distribution on log-normal (geometric mean) scale.

Figure 9. Example of Log-Normal Distribution

3.5 Calculating Delay

Let

M_T = Total number of malfunctions

D_T = Total days

$\overline{M}$ = Average number of malfunctions per day

Then

$$\overline{M} = \frac{M_T}{D_T} \qquad (5)$$

Also, let V_f = Malfunction code frequency

P_f = Probability of malfunction code

Then

$$P_f = \frac{V_f}{M_T} \qquad (6),$$

the contribution of each malfunction type to $\overline{M} = P_f \cdot \overline{M}$ (7), and the average weighted daily delay (AWDD) resulting from a malfunction type is

$$AWDD = P_f \cdot \overline{M} \cdot 220s \cdot N_E, \qquad (8)$$

where the number of affected trains per day is N_E
the total schedule delay from a malfunction, assuming it has occurred is $110s \cdot N_E$ (9).

In calculating N_E, the following assumptions were used:

- The geometric MTTR of each malfunction type equals the average time a malfunction will affect the HSR timetable,
- The proposed Chicago–St. Louis HSR trip time is 3 hr 50 min,
- The end-to-end trip time implies an average train speed of 73.2 mph, and
- 10 trains will operate daily between Chicago and St. Louis daily (5 round-trips).

Similarly, several assumptions were used in the total schedule delay, $110s \cdot N_E$:

- Under worst-case conditions, the maximum allowable train speed at a malfunctioning grade crossing is 15 mph (24 km/h),
- The train deceleration and acceleration rate is 1 mph/s (0.621 km/s),
- Train length is 500 ft (151 m), including the locomotive, and
- A typical crossing is 150 ft (45 m) in length.

Under these assumptions, a train will require 95 seconds to decelerate from 110 mph (177 km/h) to 15 mph (24 km/h), while covering a distance of 8,650 ft (2,621 m). At 15 mph (24 km/h), the train will require 30 seconds to traverse the crossing and clear the island circuit. The process is then repeated as the train accelerates back to 110 mph (177 km/h), for a total time of 220 seconds (Meyer 2001). This speed profile is illustrated in Figure 10. Conversely, a train that is not required to reduce speed will traverse the entire 17,950 ft (5,440 m) in approximately 110 seconds. The difference between the two times, 110 seconds, is the delay a train will incur due to a single malfunctioning crossing.

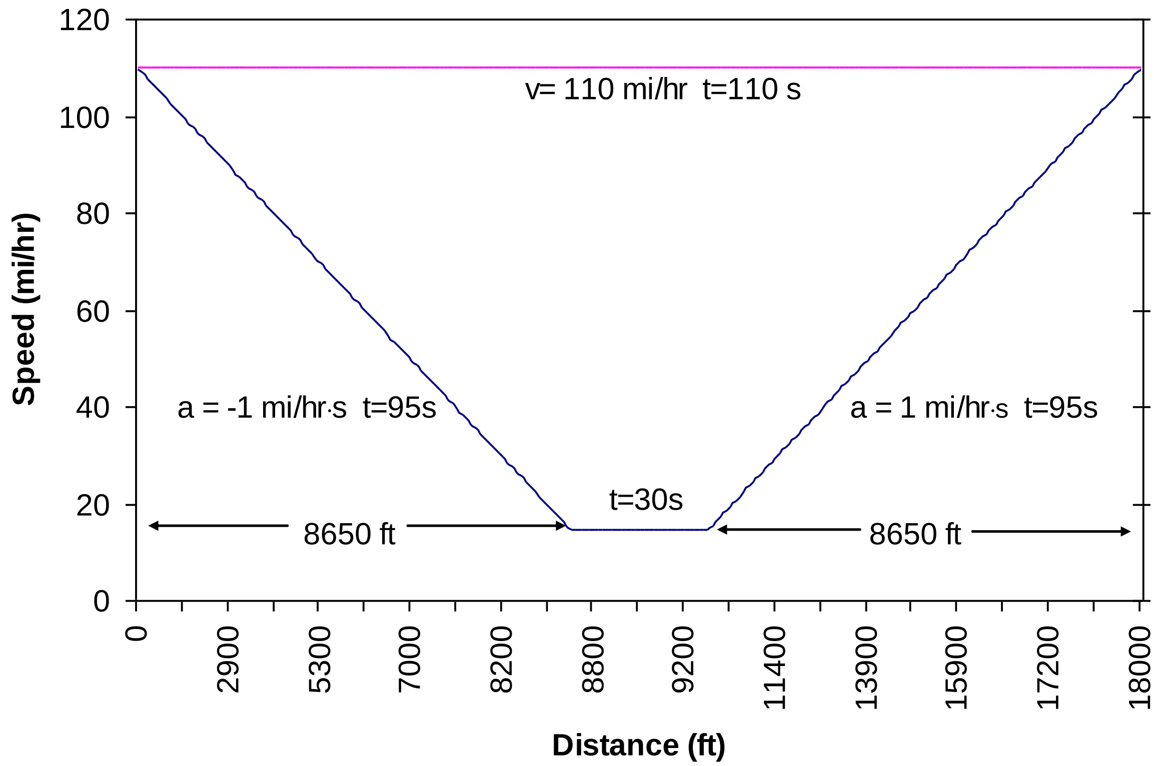


Figure 10. Speed Profile of a 110 mph Train Approaching a 15 mph Grade Crossing

N_E for each malfunction type was resolved manually by scanning the proposed HSR timetable for the interval, equal to the MTTR, in which the maximum number of trains will be present on the corridor. Because not all trains on the corridor will be affected by an individual malfunction, an approach was developed to estimate the number of trains that will experience a delay. The arrival times for each train at the four-quadrant gate crossings, shown in Appendix D, were estimated using the proposed 3 hr 50 min schedule.

For example, the MTTR for the "no cause found" malfunction type was calculated as 2 hours 11 minutes, which was rounded down to 2 hours. The maximum number of trains on the corridor for any two hour time period is five. Because the first 64 and last 106 miles (171 km) of the corridor are not in high-speed territory, only three of the five trains were found to be affected by the "no cause found" malfunction type during the 2-hour time intervals.

4 Results and Discussion

In this analysis, 889 unique malfunction tickets were recorded over 677 days, resulting in an average of 1.31 malfunctions per day. The probability of each malfunction type, ranging from $11 \cdot 10^{-4}$ to $23.2 \cdot 10^{-2}$, was calculated by applying the above delay equations to the data in Appendix E. Additionally, the total average daily delay was 10 minutes and 38 seconds, equivalent to an average of about one minute per train. Thus, on average, the impact from the malfunction codes on the HSR timetable was minimal.

The second and third columns of Table 5 show the malfunction types ranked by event frequency and probability of occurrence, unadjusted for MTTR or duration. Two types, *no cause found* and *other* were typically entered by the grade crossing maintainer when a malfunction was reported or an alarm was recorded but could not be duplicated. In many cases, the trouble tickets were related to the exit gate equipment, including improper lowering of one or more exit gates, and wind issues. Although *no cause found* and *other* were not conclusive indicators of delay to the HSR timetable, they could not be eliminated as potential predictors of future crossing equipment induced delays.

The geometric averaged weighted daily delay for each malfunction type is shown in the fourth column of Table 5. These values were calculated from the product of the event probability, the number of trains affected per day assuming a 10-train schedule, and the worst-case delay experienced by a single train from a malfunction (110 seconds). This calculation yielded a probabilistic estimate of the contribution from each malfunction to the average of 1.31 malfunctions/ day. These values, including the total average weighted delay for the entire set of malfunction types, are found in the fourth column of Table 5. The sum of the seven malfunction types responsible for approximately 80 percent of the trouble tickets contributed over 8 minutes to the total 10.5 minutes of average weighted daily delay. Assuming a 10-train daily schedule, this equates roughly to an average of one minute per train.

The last column in Table 5 is an estimate of the HSR timetable delay attributed to each malfunction event, assuming 100 percent probability of occurrence. These results typify the expected delay until a malfunction event has been resolved. Of importance is the marked difference from the average weighted delay values. More significantly, these results show that the average weighted delay, which is directly related to event probability, may not necessarily be the best measure of the impact from a malfunction. A new metric for characterizing the impact, *delay index* (DI), is presented in column 5. This is a measure of the delay incurred on the HSR timetable resulting from a particular malfunction type and is analogous to the expression for risk in safety-related research. DI is expressed as the product of the event probability, P_f, and the average weighted daily delay (eq. 8) resulting from each malfunction type. The formula,

$$DI_{AWWD} = P_f \cdot AWDD, \qquad (10)$$

is akin to the expression for risk in safety-related research, where AWDD is the severity term. Delay is often used as an alternative metric for risk. However, in this study, the delay index was employed as a means to measure the delay impact for a grade crossing malfunction, so as to maintain the distinction with the traditional definition of risk. As shown in fifth column of Table 5, the average delay term weighs the DI ranking such that the *electronics failure* and *sand, rust,* or *other deposit on rail* terms have a stronger impact on timetable delay than as a function of event frequency or probability only.

Table 5. Malfunction Events Ranked By Event Frequency

Top 20% of Malfunction Events	**Event Frequency**	**Event Probability** (%)	[*]**Average Weighted Daily Delay** (mm:ss)	**(DI_{AWDD})**
No cause found	206	23.17	1:40	38.62
Electronics failure	147	16.54	2:22	39.14
Gate mechanical failure	98	11.02	0:47	8.63
AC power failure	53	5.96	0:42	4.17
Sand, rust, or other deposit on rail	48	5.40	1:18	7.02
Gate hung up in high wind bracket/cantilever	40	4.50	0:32	2.40
Other	40	4.50	0:19	1.43
Not Dispatched	31	3.49	0:10	0.58
Planned Work	24	2.70	0:19	0.86
Gate Arm Rehung	23	2.59	0:11	0.47
Totals				
Highest 20%	**710**	**80**	**08:20**	
Remaining 80%	**179**	**20**	**02:08**	
For all types	**889**	**100.00**	**10:38**	

[*]This calculation was based on the worst-case condition of 110 s induced delay per train from the time the trouble ticket was opened until it was closed. Actual conditions may vary depending on the state of the crossing equipment and the discretion of the maintainer.

The following example illustrates how the values in Table 5 were calculated.
In this analysis,

M_T = 889

D_T = 677

So $\overline{M}$ = 889/677 = 1.31

Consider the *electronics failure* malfunction code,
where

N_E =6 trains

MTTR = 9 hr 55 min

3 hr 50 min Chicago-St. Louis high-speed rail schedule

Average train speed of $73.2\, mi/hr$ on the corridor

10 daily trains.

In this case, V_f =147, yielding P_f =147/889 = 0.1654

The average weighted delay is the product of $P_f \cdot \overline{M} \cdot 110s \cdot N_E$, = (0.1654)(1.31)(110)(6), approximately 143s or 2 min 23 sec.

An alternative approach to ranking the impact of malfunctions is presented in

Table **6** with DI now expressed as a function of MTTR. Although not a direct measure of delay to the HSR timetable, MTTR is a strong predictor. Here, the delay index is expressed as $DI_{MTTRR} = P_f \cdot MTTR$**,** where MTTR is the severity term. Under this scenario, lower probability events with large MTTR values may generate a significantly higher DI rank than frequently occurring events. These low probability events may also occur concurrently at multiple grade crossings, potentially resulting in an amplification of the impact on the HSR timetable.

Consider the case of *sand, rust*, or *other deposit on rail*, with a DI_{MTTR} of 896. This malfunction type could potentially result in loss of shunt and, under worst-case conditions, yield a significant delay. Factors such as the number of impacted crossings and the repair time are highly variable and could cause the effect on the HSR timetable to vary significantly. Although the P_f for this malfunction type (5.40 percent) is in the lower tier of the most frequently occurring malfunction types, the MTTR of about 166 hr is the highest of all types. A widespread episode of loss of shunt occurred during a two week period 2004 in which virtually all of the *sand, rust*, or *other deposit on rail* trouble tickets were recorded. The shunt loss encompassed a 25-mile (40 km) segment of the corridor, including 30 four-quadrant grade crossings. This resulted in the issuance of 30 trouble tickets and a 15 mph (24 km/h) temporary speed restriction at the crossings between August 30 and September 13, 2004. For the 30 trouble tickets, the MTTR was approximately 272 hours. For the proposed HSR timetable, an estimated 115 trains were calculated to be delayed, with the typical train experiencing a delay of almost 55 minutes. These values contrast strongly with the MTTR estimate over the 2-year evaluation period of 166 hours and an average weighted daily delay of 1 minute 18 seconds.

Table 6. Malfunction Events Ranked by DI_{MTTR}

Top 10 Malfunctions Based on Delay Index Ranking	Event Frequency	Event Probability (%)	MTTR (hh:mm:ss)	(DI_{MTTR})
Sand, rust, or other deposit on rail	48	5.40	165:57:41	896.04
Electronics failure	147	16.54	9:55:26	164.05
No cause found	206	23.17	2:10:59	50.35
Salt/ice in crossing	13	1.46	30:35:33	44.44
AC power failure	53	5.96	6:53:25	41.04
Card/electronic component replace/repair	14	1.57	17:56:55	28.15
Gate mechanical failure	98	11.02	2:10:45	24.01
Broken/damaged equipment	8	0.90	19:55:11	17.55
Open/shorted underground	2	0.22	78:56:10	17.45
Planned work	24	2.70	6:06:28	16.29

Another malfunction episode that impacted railroad operations occurred during a single day. On Wednesday, November 24, 2004, Central Illinois was severely impacted by a winter storm. Several inches of heavy wet snow fell and changed to ice. The recovery effort was hindered by wind speeds over 50 mph (80 km/h) and rapidly falling temperatures. This resulting damage included downed power lines, trees, and utility poles. The downed transmission lines resulted in loss of power to several electrical substations, impacting large areas of Central Illinois.[3]

A total of seven malfunction types, resulting in 31 trouble tickets, were issued at 29 different grade crossings during the 24-hour period in which the storm impacted Central Illinois. The MTTR for these events was approximately 23 hours. For the proposed HSR timetable, an estimated 10 trains would be delayed, with a single train potentially experiencing a delay of almost 53 minutes. However, numerous delays occurred during the day of the storm that impacted the Amtrak timetable.

Table 7 illustrates the occurrence of malfunction events from November 24–25, 2004. The second column shows that two malfunction types, *AC power failure* and *gate mechanical* contributed to 23 of the 31 trouble tickets. This was equivalent to almost 75 percent of the trouble tickets issued. As shown in the third column of

Table 7, the incidence of these two malfunction types during the snow and ice storm was disproportionate to their overall weight in the general population of Data Set II. The most plausible explanation for this discrepancy is that these malfunction events were a direct result of the snow and ice storm, especially in light of the trouble ticket descriptors supplied by the railroad signal maintainers. The descriptors included *commercial power failure, snow on the*

[3] http://www.menard.com/Nov.%2004%20Storm.htm

island circuit, *ice and snow on gate arms*, and *high winds preventing the exit gates from ascending*.

Table 7. Trouble Tickets Issued on 11/24 -11/25 of 2004

Malfunction Event	Event Frequency	Event Probability (%)	Data Set II Event Probability (%)
AC power failure	18	58.1	5.96
Gate mechanical failure	5	16.1	11.02
Other	4	12.9	5.40
Replaced/repaired gate	1	3.2	0.90
Gate hung up in high wind bracket/cantilever	1	3.2	4.50
Wet/bad ballast	1	3.2	0.79
No cause found	1	3.2	23.17
Total	**31**		

5 Conclusions

HSR corridors are usually green-field developed dedicated rights-of-way with grade separated highway-rail crossings or no crossings at all. However, this optimal state is not always possible, especially with incremental HSR deployments. The Illinois HSR corridor, currently under development between Chicago and St. Louis, is typical of such a system, where rail corridors are upgraded incrementally from the conventional passenger rail speed of 79 mph to 90, 110, 125, and eventually 150 mph. Whereas other mechanisms of risk such as inferior signaling systems and track can easily be mitigated, highway-rail grade crossings are particularly problematic if they cannot be grade separated or closed. One promising treatment, which involves upgrading conventional dual-gate crossings to four-quadrant gate systems with inductive loop vehicle detection, has been successfully implemented at eight grade crossings on Amtrak's NEC system in Connecticut.

The Illinois implementation, featuring 69 four-quadrant gate/vehicle detection systems over a span of 120 miles (193 km), represents the largest installation of this technology to date on a HSR system. The purpose of this research was to evaluate the timetable impact, if any, from the reliability of the 69 four-quadrant gate/vehicle detection systems installed on the future Illinois HSR corridor. Since a HSR timetable was not in existence, the authors constructed a representative "best-guess" estimate that is a synthesis of likely one-way trip timetables and daily round-trip frequencies published in the public domain.

Equipment reliability was determined using a probabilistic model developed by applying statistical analysis to identify trends in grade crossing equipment trouble tickets. The 37 malfunction types were sorted by type, frequency (which was used to derive probability), and resolution time (which was used to calculate MTTR). The weighted probabilities of occurrence and MTTR for each malfunction type were used to calculate the impact of the four-quadrant gate/vehicle detection system on the proposed high-speed timetable.

The total average daily delay is 10 minutes and 38 seconds, equivalent to an estimated average of one minute per train for a 10-train daily schedule. As such, the reliability of the four-quadrant gate/vehicle detection system will incur minimal impact on the HSR timetable. However, some interesting insights resulted from this research. First**,** the majority of trouble tickets were related to the maintenance of railroad signaling system components that are interconnected with the grade crossing electronics and not an indication of the four-quadrant gate/vehicle detection system reliability. Moreover, an overwhelming majority of crossing malfunctions equally impacted operations of both the entrance and exit gate equipment. However, the malfunction or improper operation of a small subset of components was predicted to result in potentially prolonged disruptions to passenger rail operations. These low probability events may occur concurrently at multiple grade crossings, potentially resulting in an amplification of the impact on the HSR timetable.

Second, analysis of trouble ticket data can be used to identify recurring maintenance issues that may require further study. This may eventually lead to optimization of railroad inspection and maintenance procedures. Railroad inspection and maintenance procedures have been modified to minimize the frequency and impact of these events. Fortunately, longitudinal analysis of maintenance data will facilitate identification of such long-term trends. On the basis of this research, railroad and state engineers will be able to review and, if necessary, modify maintenance procedures to optimize operation of the four-quadrant gate technology.

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Appendix A

Locations of Four-Quadrant Crossings.

(49 that support HSR operations highlighted in red)

Milepost Mile (km)	Crossing Number	Crossing Name	Location	County	Maximum Speed mph (km/h)
64.07 (103.17)	290 517Y	Storm Road	near Gardner	Grundy	79 (127)
64.36 (103.63)	290 518F	Washington St.	in Gardner	Grundy	79 (127)
64.47 (103.81)	290 519M	Division St.	in Gardner	Grundy	79 (127)
64.63 (104.07)	290 521N	Jackson /Jefferson St	in Gardner	Grundy	79 (127)
64.75 (104.26)	290 522V	Main St.	in Gardner	Grundy	79 (127)
65.50 (105.47)	290 525R	Maher Rd.	near Gardner	Grundy	79 (127)
66.91 (107.74)	290 527E	Gorman Rd.	near Gardner	Grundy	79 (127)
69.09 (111.25)	290 531U	Stonewall Rd.	near Dwight	Grundy	79 (127)
70.52 (113.55)	290 533H	Scully Rd.	near Dwight	Grundy	79 (127)
71.14 (114.55)	290 534P	Mazon Rd.	near Dwight	Grundy	79 (127)
71.95 (115.86)	290 535W	Livingston Rd.	near Dwight	Livingston	79 (127)
74.93 (120.66)	290 729C	TR 19B	near Dwight	Livingston	79 (127)
75.93 (122.27)	290 730W	TR 220	near Dwight	Livingston	79 (127)
76.88 (123.80)	290 732K	TR 216B (2400E)	near Dwight	Livingston	79 (127)
78.96 (127.14)	290 734Y	TR 41C (2800N)	near Odell	Livingston	110 (177)
80.21 (129.16)	290 735F	TR 47B (2700N)	near Odell	Livingston	110 (177)
81.43 (131.12)	290 736M	Prairie St.	in Odell	Livingston	110 (177)
81.52 (131.27)	290 737U	Scott St.	in Odell	Livingston	110 (177)
81.65 (131.48)	290 738B	Tremont St.	in Odell	Livingston	110 (177)
81.72 (131.59)	290 739H	Hamilton St.	in Odell	Livingston	110 (177)
82.69 (133.15)	290 742R	TR 69	near Odell	Livingston	110 (177)
86.92 (139.96)	290 747A	Main St.	in Cayuga	Livingston	110 (177)
88.90 (143.15)	290 748G	TR 113A/Bunge Rd.	near Cayuga	Livingston	110 (177)
95.85 (154.34)	290 765X	TR 159 (1400N)	near Chenoa	Livingston	110 (177)
98.08 (157.93)	290 770U	CR 8	near Chenoa	Livingston	110 (177)
99.20 (159.74)	290 771B	TR 195A	near Chenoa	Livingston	110 (177)
100.87 (162.43)	290 774W	TR 209	near Chenoa	Livingston	110 (177)
101.44 (163.34)	290 775D	TR 1B (Co. Line Rd.)	near Chenoa	McLean	110 (177)
102.04 (164.31)	290 776K	Division St.	in Chenoa	McLean	110 (177)
102.37 (164.84)	290 779F	Owsley St.	in Chenoa	McLean	110 (177)
102.57 (165.16)	290 780A	US 24 (Cemetery St.)	in Chenoa	McLean	110 (177)
103.69 (166.97)	290 781G	TR 23A (3000N)	near Chenoa	McLean	40 (64)
105.93 (170.57)	290 786R	TR 35A	near Chenoa	McLean	40 (64)
108.90 (175.36)	290 790F	Orange St	near Lexington	McLean	40 (64)

Milepost Mile (km)	Crossing Number	Crossing Name	Location	County	Maximum Speed mph (km/h)
110.10 (177.29)	290 791M	North St.	in Lexington	McLean	110 (177)
110.27 (177.56)	290 792U	Main St.	in Lexington	McLean	110 (177)
110.36 (177.71)	290 793B	Chestnut St.	in Lexington	McLean	110 (177)
111.65 (179.79)	290 794H	TR 83	near Lexington	McLean	110 (177)
113.49 (182.75)	290 795P	Killian Rd.	near Lexington	McLean	99 (159)
115.18 (185.47)	290 798K	TR 358A	near Towanda	McLean	99 (159)
118.12 (190.20)	290 801R	Madison St.	in Towanda	McLean	99 (159)
118.25 (190.41)	290 802X	Jefferson St.	in Towanda	McLean	99 (159)
120.03 (193.28)	290 803E	TR 306A / Airport Rd	near Towanda	McLean	99 (159)
127.19 (204.81)	290 949X	Miller St.	in Bloomington	McLean	110 (177)
128.09 (206.26)	290 950S	Six Points Rd.	near Bloomington	McLean	110 (177)
133.70 (215.29)	290 955B	TR 443	near Bloomington	McLean	79 (127)
136.35 (219.56)	290 957P	Funks Grove Rd.	near McLean	McLean	79 (127)
139.12 (224.02)	290 960X	TR 533	near McLean	McLean	79 (127)
140.91 (226.90)	290 962L	Railroad Ave.	in McLean	McLean	110 (177)
141.16 (227.31)	290 964A	US 136	in McLean	McLean	110 (177)
143.72 (231.43)	290 967V	TR 38	near Atlanta	McLean	110 (177)
145.75 (234.70)	290 971K	Elm St.	in Atlanta	Logan	110 (177)
145.81 (234.79)	290 972S	Vine St.	in Atlanta	Logan	110 (177)
145.85 (234.86)	290 973Y	Race St.	in Atlanta	Logan	110 (177)
147.60 (237.68)	290 975M	Lazy Row Rd./TR 51	near Atlanta	Logan	110 (177)
149.75 (241.14)	290 977B	Main St.	in Lawndale	Logan	110 (177)
150.15 (241.78)	290 978H	Lincoln St.	in Lawndale	Logan	110 (177)
152.18 (245.05)	290 980J	TR 222	near Lincoln	Logan	110 (177)
153.46 (247.11)	290 982X	TR 93	near Lincoln	Logan	110 (177)
159.40 (256.68)	294 260E	TR 128 / Prison Road	near Lincoln	Logan	110 (177)
161.30 (259.74)	294 261L	TR 149A	near Broadwell	Logan	110 (177)
163.45 (263.20)	294 263A	Main St.	in Broadwell	Logan	110 (177)
167.30 (269.40)	294 267C	Ogelsby St.	in Elkhart	Logan	110 (177)
168.50 (271.33)	294 269R	TR 199A	near Elkhart	Logan	110 (177)
169.80 (273.42)	294 270K	TR 50A	near Williamsville	Logan	110 (177)
172.35 (277.53)	294 272Y	TR 5	near Williamsville	Sangamon	110 (177)
173.00 (278.58)	294 275U	Main St.	in Williamsville	Sangamon	110 (177)
176.70 (284.54)	294 280R	TR 33/Wolf Rd.	near Sherman	Sangamon	110 (177)
177.87 (286.42)	294 281X	Andrew Rd.	in Sherman	Sangamon	110 (177)

Appendix B

Sample Trouble Ticket Report

```
Ticket #        : XXXXXXXXX
CallerType      : MAXM
Rptr Name       :
Credible?       : N
Occur D/T       : 5/9/2003 12:30:59
Dispatched      : 5/9/2003 15:42:34
Hold4Mon        : 5/13/2003 17:17:33
Hold4Parts      : 5/9/2003 16:53:40
Temp Fix Date   :
Closed Date     : 5/13/2003 17:18:27
MP Prefix       : 0
MP              : 064.7500
Status          : CLOSED
Control Point   :
DOT             : 290522V
Subdiv Nbr      : 025
Sub Name        : JOLIET
Location        : MAIN ST
City            : GARDNER
Description     : HIGH PRIORITY ALARM.../AWK/
Gang Nbr        : 8294
Mtnr Name       : XXXXXXX
MSM Nbr         : 0785
MSM Name        : XXXXXXX
Dept. Cd        : 1
Equip Cd        : 3
FRA Cd          : 2
Resolution Cd   : 74
Repair Descr    : 74 Electronics Failure  -- MTR REPORTS THAT EXIT GATES
WILL NOT
   COME DOWN UNTIL ENTRANCE GATES ARE HORIZONTAL, , ET REPLACED THE A&E
   LOOP PROCCESSOR..CMS
Agency          :
PD Notify       :
Req Dispatcher  :
Req Date (XH)   :
Rel Dispatcher  :
Rel Date (XH)   :
Req Dispatcher  :
Req Date (XG)   :
Rel Dispatcher  :
Rel Date (XG)   :
XS DispatchReq  :
XS DispatchReL  :
Work Log        : 5/9/2003 12:31:53 EENG384
   Changed Status to: PAGED -  8294

   5/9/2003 14:31:31 EENG384
   REPAGED MTR SANDAGE../AWK/

   5/9/2003 15:42:37 ENGB440
   Changed Status to: DISPATCHED -  8294

   5/9/2003 16:53:43 ENGB440
   Changed Status to: HOLD4PARTS -  Test Made: 234.257 System
   operation.8294
```

Appendix C

Letter of Request to Union Pacific Railroad

U.S. Department
of Transportation

**Federal Railroad
Administration**

1120 Vermont Ave., N.W.
Washington, D.C. 20590

RCVD 4/29/05

Mr. William Breeden
Director Signal Engineering
Union Pacific Railroad
1400 Douglas Street STOP 0910
Omaha, NE 68179

Dear Mr. Breeden:

Thank you for your generous offer to provide the Trouble Ticket reports for the four-quadrant gate/vehicle detection technology installed at 69 crossings on the Illinois high-speed rail (HSR) corridor in conjunction with the North American Joint Positive Train Control program. As we discussed, the Federal Railroad Administration (FRA) is conducting research to characterize the operational performance of the integrated four-quadrant gate grade crossing/inductive loop vehicle detection systems. The Volpe National Transportation Systems Center is supporting the FRA in this effort.

This data is relevant to determining the frequency and nature of grade crossing equipment malfunctions, and estimating the impact of these malfunctions on the current railroad timetable and the proposed HSR timetable.

This is the formal request for copies of these reports, submitted at your earliest convenience, and any other ancillary information that will improve the accuracy of this research effort. Please send the reports to:

Mr. Adrian Hellman
Volpe National Transportation Systems Center
Mail Stop DTS-75
55 Broadway
Cambridge, MA 02142

If there are any questions on this request, please contact Jim Smailes at (202) 493-6360, james.smailes@fra.dot.gov or Mr. Adrian Hellman, Volpe Center, at (617) 494-2171, 617-494-2318 (fax), or hellman@volpe.dot.gov.

Sincerely,

Jo Strang
Deputy Associate Administrator
For Railroad Development

Appendix D

Estimated Arrival Times of High-Speed Trains at Four-Quadrant Gate Crossings

	Read Down					Read Up				
M.P	Train 1	Train 2	Train 3	Train 4	Train 5	Train 6	Train 7	Train 8	Train 9	Train 10
Chicago	6:45 AM	8:15 AM	3:20 PM	5:15 PM	7:15 PM	8:25 AM	10:25 AM	12:20 PM	7:00 PM	9:00 PM
64.07	7:37 AM	9:07 AM	4:12 PM	6:07 PM	8:07 PM	7:32 AM	9:32 AM	11:27 AM	6:07 PM	8:07 PM
64.36	7:37 AM	9:07 AM	4:12 PM	6:07 PM	8:07 PM	7:31 AM	9:31 AM	11:26 AM	6:06 PM	8:06 PM
64.47	7:37 AM	9:07 AM	4:12 PM	6:07 PM	8:07 PM	7:31 AM	9:31 AM	11:26 AM	6:06 PM	8:06 PM
64.63	7:37 AM	9:07 AM	4:12 PM	6:07 PM	8:07 PM	7:31 AM	9:31 AM	11:26 AM	6:06 PM	8:06 PM
64.75	7:37 AM	9:07 AM	4:12 PM	6:07 PM	8:07 PM	7:31 AM	9:31 AM	11:26 AM	6:06 PM	8:06 PM
65.50	7:38 AM	9:08 AM	4:13 PM	6:08 PM	8:08 PM	7:31 AM	9:31 AM	11:26 AM	6:06 PM	8:06 PM
66.91	7:39 AM	9:09 AM	4:14 PM	6:09 PM	8:09 PM	7:29 AM	9:29 AM	11:24 AM	6:04 PM	8:04 PM
69.09	7:41 AM	9:11 AM	4:16 PM	6:11 PM	8:11 PM	7:28 AM	9:28 AM	11:23 AM	6:03 PM	8:03 PM
70.52	7:42 AM	9:12 AM	4:17 PM	6:12 PM	8:12 PM	7:26 AM	9:26 AM	11:21 AM	6:01 PM	8:01 PM
71.14	7:42 AM	9:12 AM	4:17 PM	6:12 PM	8:12 PM	7:26 AM	9:26 AM	11:21 AM	6:01 PM	8:01 PM
71.95	7:43 AM	9:13 AM	4:18 PM	6:13 PM	8:13 PM	7:25 AM	9:25 AM	11:20 AM	6:00 PM	8:00 PM
74.93	7:45 AM	9:15 AM	4:20 PM	6:15 PM	8:15 PM	7:23 AM	9:23 AM	11:18 AM	5:58 PM	7:58 PM
75.93	7:46 AM	9:16 AM	4:21 PM	6:16 PM	8:16 PM	7:22 AM	9:22 AM	11:17 AM	5:57 PM	7:57 PM
76.88	7:47 AM	9:17 AM	4:22 PM	6:17 PM	8:17 PM	7:21 AM	9:21 AM	11:16 AM	5:56 PM	7:56 PM
78.96	7:49 AM	9:19 AM	4:24 PM	6:19 PM	8:19 PM	7:20 AM	9:20 AM	11:15 AM	5:55 PM	7:55 PM
80.21	7:50 AM	9:20 AM	4:25 PM	6:20 PM	8:20 PM	7:19 AM	9:19 AM	11:14 AM	5:54 PM	7:54 PM
81.43	7:51 AM	9:21 AM	4:26 PM	6:21 PM	8:21 PM	7:18 AM	9:18 AM	11:13 AM	5:53 PM	7:53 PM
81.52	7:51 AM	9:21 AM	4:26 PM	6:21 PM	8:21 PM	7:17 AM	9:17 AM	11:12 AM	5:52 PM	7:52 PM
81.65	7:51 AM	9:21 AM	4:26 PM	6:21 PM	8:21 PM	7:17 AM	9:17 AM	11:12 AM	5:52 PM	7:52 PM
81.72	7:51 AM	9:21 AM	4:26 PM	6:21 PM	8:21 PM	7:17 AM	9:17 AM	11:12 AM	5:52 PM	7:52 PM
82.69	7:52 AM	9:22 AM	4:27 PM	6:22 PM	8:22 PM	7:17 AM	9:17 AM	11:12 AM	5:52 PM	7:52 PM
86.92	7:55 AM	9:25 AM	4:30 PM	6:25 PM	8:25 PM	7:13 AM	9:13 AM	11:08 AM	5:48 PM	7:48 PM
88.90	7:57 AM	9:27 AM	4:32 PM	6:27 PM	8:27 PM	7:11 AM	9:11 AM	11:06 AM	5:46 PM	7:46 PM
95.85	8:02 AM	9:32 AM	4:37 PM	6:32 PM	8:32 PM	7:06 AM	9:06 AM	11:01 AM	5:41 PM	7:41 PM
98.08	8:04 AM	9:34 AM	4:39 PM	6:34 PM	8:34 PM	7:04 AM	9:04 AM	10:59 AM	5:39 PM	7:39 PM
99.20	8:05 AM	9:35 AM	4:40 PM	6:35 PM	8:35 PM	7:03 AM	9:03 AM	10:58 AM	5:38 PM	7:38 PM
100.87	8:07 AM	9:37 AM	4:42 PM	6:37 PM	8:37 PM	7:02 AM	9:02 AM	10:57 AM	5:37 PM	7:37 PM
101.44	8:07 AM	9:37 AM	4:42 PM	6:37 PM	8:37 PM	7:01 AM	9:01 AM	10:56 AM	5:36 PM	7:36 PM
102.04	8:07 AM	9:37 AM	4:42 PM	6:37 PM	8:37 PM	7:01 AM	9:01 AM	10:56 AM	5:36 PM	7:36 PM
102.37	8:08 AM	9:38 AM	4:43 PM	6:38 PM	8:38 PM	7:01 AM	9:01 AM	10:56 AM	5:36 PM	7:36 PM
102.57	8:08 AM	9:38 AM	4:43 PM	6:38 PM	8:38 PM	7:00 AM	9:00 AM	10:55 AM	5:35 PM	7:35 PM
103.69	8:09 AM	9:39 AM	4:44 PM	6:39 PM	8:39 PM	6:59 AM	8:59 AM	10:54 AM	5:34 PM	7:34 PM
105.93	8:11 AM	9:41 AM	4:46 PM	6:41 PM	8:41 PM	6:58 AM	8:58 AM	10:53 AM	5:33 PM	7:33 PM
108.90	8:13 AM	9:43 AM	4:48 PM	6:43 PM	8:43 PM	6:55 AM	8:55 AM	10:50 AM	5:30 PM	7:30 PM
110.10	8:14 AM	9:44 AM	4:49 PM	6:44 PM	8:44 PM	6:54 AM	8:54 AM	10:49 AM	5:29 PM	7:29 PM
110.27	8:14 AM	9:44 AM	4:49 PM	6:44 PM	8:44 PM	6:54 AM	8:54 AM	10:49 AM	5:29 PM	7:29 PM
110.36	8:14 AM	9:44 AM	4:49 PM	6:44 PM	8:44 PM	6:54 AM	8:54 AM	10:49 AM	5:29 PM	7:29 PM
111.65	8:15 AM	9:45 AM	4:50 PM	6:45 PM	8:45 PM	6:53 AM	8:53 AM	10:48 AM	5:28 PM	7:28 PM
113.49	8:17 AM	9:47 AM	4:52 PM	6:47 PM	8:47 PM	6:52 AM	8:52 AM	10:47 AM	5:27 PM	7:27 PM
115.18	8:18 AM	9:48 AM	4:53 PM	6:48 PM	8:48 PM	6:50 AM	8:50 AM	10:45 AM	5:25 PM	7:25 PM
118.12	8:21 AM	9:51 AM	4:56 PM	6:51 PM	8:51 PM	6:48 AM	8:48 AM	10:43 AM	5:23 PM	7:23 PM
118.25	8:21 AM	9:51 AM	4:56 PM	6:51 PM	8:51 PM	6:48 AM	8:48 AM	10:43 AM	5:23 PM	7:23 PM
120.03	8:22 AM	9:52 AM	4:57 PM	6:52 PM	8:52 PM	6:46 AM	8:46 AM	10:41 AM	5:21 PM	7:21 PM
127.19	8:28 AM	9:58 AM	5:03 PM	6:58 PM	8:58 PM	6:40 AM	8:40 AM	10:35 AM	5:15 PM	7:15 PM

M.P	Read Down Train 1	Train 2	Train 3	Train 4	Train 5	Read Up Train 6	Train 7	Train 8	Train 9	Train 10
128.09	8:29 AM	9:59 AM	5:04 PM	6:59 PM	8:59 PM	6:40 AM	8:40 AM	10:35 AM	5:15 PM	7:15 PM
133.70	8:33 AM	10:03 AM	5:08 PM	7:03 PM	9:03 PM	6:35 AM	8:35 AM	10:30 AM	5:10 PM	7:10 PM
136.35	8:35 AM	10:05 AM	5:10 PM	7:05 PM	9:05 PM	6:33 AM	8:33 AM	10:28 AM	5:08 PM	7:08 PM
139.12	8:38 AM	10:08 AM	5:13 PM	7:08 PM	9:08 PM	6:31 AM	8:31 AM	10:26 AM	5:06 PM	7:06 PM
140.91	8:39 AM	10:09 AM	5:14 PM	7:09 PM	9:09 PM	6:29 AM	8:29 AM	10:24 AM	5:04 PM	7:04 PM
141.16	8:39 AM	10:09 AM	5:14 PM	7:09 PM	9:09 PM	6:29 AM	8:29 AM	10:24 AM	5:04 PM	7:04 PM
143.72	8:41 AM	10:11 AM	5:16 PM	7:11 PM	9:11 PM	6:27 AM	8:27 AM	10:22 AM	5:02 PM	7:02 PM
145.75	8:43 AM	10:13 AM	5:18 PM	7:13 PM	9:13 PM	6:25 AM	8:25 AM	10:20 AM	5:00 PM	7:00 PM
145.81	8:43 AM	10:13 AM	5:18 PM	7:13 PM	9:13 PM	6:25 AM	8:25 AM	10:20 AM	5:00 PM	7:00 PM
145.85	8:43 AM	10:13 AM	5:18 PM	7:13 PM	9:13 PM	6:25 AM	8:25 AM	10:20 AM	5:00 PM	7:00 PM
147.60	8:45 AM	10:15 AM	5:20 PM	7:15 PM	9:15 PM	6:24 AM	8:24 AM	10:19 AM	4:59 PM	6:59 PM
149.75	8:46 AM	10:16 AM	5:21 PM	7:16 PM	9:16 PM	6:22 AM	8:22 AM	10:17 AM	4:57 PM	6:57 PM
150.15	8:47 AM	10:17 AM	5:22 PM	7:17 PM	9:17 PM	6:22 AM	8:22 AM	10:17 AM	4:57 PM	6:57 PM
152.18	8:48 AM	10:18 AM	5:23 PM	7:18 PM	9:18 PM	6:20 AM	8:20 AM	10:15 AM	4:55 PM	6:55 PM
153.46	8:49 AM	10:19 AM	5:24 PM	7:19 PM	9:19 PM	6:19 AM	8:19 AM	10:14 AM	4:54 PM	6:54 PM
159.40	8:54 AM	10:24 AM	5:29 PM	7:24 PM	9:24 PM	6:14 AM	8:14 AM	10:09 AM	4:49 PM	6:49 PM
161.30	8:56 AM	10:26 AM	5:31 PM	7:26 PM	9:26 PM	6:13 AM	8:13 AM	10:08 AM	4:48 PM	6:48 PM
163.45	8:57 AM	10:27 AM	5:32 PM	7:27 PM	9:27 PM	6:11 AM	8:11 AM	10:06 AM	4:46 PM	6:46 PM
167.30	9:01 AM	10:31 AM	5:36 PM	7:31 PM	9:31 PM	6:08 AM	8:08 AM	10:03 AM	4:43 PM	6:43 PM
168.50	9:01 AM	10:31 AM	5:36 PM	7:31 PM	9:31 PM	6:07 AM	8:07 AM	10:02 AM	4:42 PM	6:42 PM
169.80	9:03 AM	10:33 AM	5:38 PM	7:33 PM	9:33 PM	6:06 AM	8:06 AM	10:01 AM	4:41 PM	6:41 PM
172.35	9:05 AM	10:35 AM	5:40 PM	7:35 PM	9:35 PM	6:04 AM	8:04 AM	9:59 AM	4:39 PM	6:39 PM
173.00	9:05 AM	10:35 AM	5:40 PM	7:35 PM	9:35 PM	6:03 AM	8:03 AM	9:58 AM	4:38 PM	6:38 PM
176.70	9:08 AM	10:38 AM	5:43 PM	7:38 PM	9:38 PM	6:00 AM	8:00 AM	9:55 AM	4:35 PM	6:35 PM
177.87	9:09 AM	10:39 AM	5:44 PM	7:39 PM	9:39 PM	5:59 AM	7:59 AM	9:54 AM	4:34 PM	6:34 PM
St. Louis	10:35 AM	12:05 PM	7:10 PM	9:05 PM	11:05 PM	4:35 AM	6:35 AM	8:30 AM	3:10 PM	5:10 PM

Appendix E

Breakdown of Trouble Tickets by Malfunction Type

Code	Description	Total Frequency	Probability (%)	Average Time to fix (Geometric (hh:mm:ss)
1	No Cause Found	206	23.17%	2:10:59
74	Electronics Failure	147	16.54%	9:55:26
91	Gate Mechanical Failure	98	11.02%	2:10:45
57	AC Power Failure	53	5.96%	6:53:25
39	Sand, Rust, Or Other Deposit On Rail	48	5.40%	165:57:41
2	Other	40	4.50%	1:44:34
29	Gate Hung Up In High Wind Bracket/Cantilever	40	4.50%	3:34:00
7	Not Dispatched	31	3.49%	0:34:43
3	Planned Work	24	2.70%	6:06:28
92	Rehung Gate Arm	23	2.59%	2:06:31
90	Replace/Rebuild Gate Arm	21	2.36%	2:17:21
72	Open/Short Circuit	19	2.14%	2:49:28
75	Electronics Adjust	15	1.69%	1:29:56
99	Card/Electronic Component Replace/Repair	14	1.57%	17:56:55
27	Salt/Ice in Crossing	13	1.46%	30:35:33
70	Lightning Arrestor	12	1.35%	5:27:37
58	Blown Fuse/Breaker Trip	11	1.24%	1:33:21
37	Track Circuit Occupied	9	1.01%	1:45:30
69	Broken/Damaged Equipment	8	0.90%	1:33:34
28	Replace/Repair Gate Arm Light(S)/Cord	8	0.90%	19:55:11
35	Wet/Bad Ballast	7	0.79%	3:08:50
30	Broken/High Resistance Bond	7	0.79%	17:28:03
31	Broken Track Wire	6	0.67%	2:05:58
62	Snow/Ice	5	0.56%	2:20:14
15	Damage By Vehicle	4	0.45%	18:21:20
34	Insulated Joint Failure	3	0.34%	3:21:27
36	Shorted Track Circuit	3	0.34%	43:54:06
52	Open/Shorted Underground	2	0.22%	2:44:26
40	Battery Failure	2	0.22%	6:07:25
77	B/O Relay	2	0.22%	78:56:10
104	Human Failure/Intervention	1	0.11%	0:20:00
78	Burned Out/Bad Bulb	1	0.11%	1:48:00
16	High Wind Damaged	1	0.11%	1:54:00
109	Commercial Power Interference	1	0.11%	3:33:00
43	Rectifier Failure	1	0.11%	3:44:00
0	Testing	1	0.11%	6:29:00
71	Resistance Unit	1	0.11%	9:06:00
38	Track Circuit Adjustment	1	0.11%	13:00:00