# Train Delay and Economic Impact of In-Service Failures of Railroad Rolling Stock

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**Railcar condition directly affects the safety, the efficiency, and the reliability of freight railroad operations. Current railcar inspection practices are intended to identify defects before failure, but these practices generally do not enable preventive maintenance because manual, visual inspection is inherently limited. As a result, automated wayside condition-monitoring technologies have been developed to monitor rolling stock condition and facilitate predictive maintenance strategies. Improving the effectiveness of monitoring of railcar conditions could substantially reduce in-service failures and derailments, operational waste, and variability in rail operations and could enhance network productivity, capacity, and reliability. An analysis of the effect of lean production methods on main-line railway operations was conducted to determine the potential impact of improved railcar inspection and maintenance practices made possible by new, automated wayside technologies. Dispatch simulation software was used to quantify the magnitude and the variability of train delay as a function of both traffic level and severity of service outage. The results indicated that the annual cost caused by main-line delay was substantial compared with the annual cost of track and equipment damages from main-line derailments caused by mechanical causes. This work provided an analytical framework to assess the potential cost savings available through improved preventive maintenance strategies.**

Since the early 1990s the U.S. railroad industry has made substantial investments in wayside detection systems capable of monitoring the condition of freight car components. From 1993 to 2008, U.S. Class I railroads spent over $70 million on the development, installation, and maintenance of these systems (*1*). Previous economic analyses have justified these investments on the basis of the cost savings that resulted from a reduction in derailments. However, additional benefits associated with the reduction in main-line in-service failures (ISFs) should also be considered. An ISF occurs when a train stops on the main line because of a track or equipment defect. Although ISFs generally result in shorter, less costly delays than derailments, they occur much more frequently. U.S. Class I railroads experience thousands of equipment-caused ISFs per year; in contrast, the frequency of equipment-caused derailments ranges from 100 to 150 per year (*2*). Thus, ISFs have a considerable financial impact caused by both the direct and indirect costs of main-line train delay.

To assess the economic impact of equipment-related ISFs, lean production principles were applied to railcar inspection and maintenance practices to determine the potential for both direct and indirect cost savings. Direct cost savings were addressed through an analysis of train delay, and indirect savings were addressed by analyzing the variability associated with train delay.

## AUTOMATED CONDITION-MONITORING TECHNOLOGY

Manual railcar inspections vary in their efficiency and effectiveness depending on inspection conditions and the experience or ability of individual car inspectors. A train may be inspected to the best ability of a particular car inspector, yet defects may be missed. Recognizing the inefficiency and subjectivity of manual inspection, the railroad industry has developed technologies to augment the efforts of human inspectors. These systems use various sensing mechanisms to measure heat, force, sound, and visual parameters in order to monitor the condition of railcar components. The technical maturity of these systems ranges from well established and in wide use by the industry for decades to systems that are still under development.

The first wayside detection systems were designed to identify defective components on passing trains in order to prevent derailments. Developed from the 1930s through the 1950s, these early technologies (e.g., hot bearing detectors and dragging-equipment detectors) provided a reactive means of defect detection, requiring a train to stop on the main line if a serious defect was identified (*3–8*). Although still widely used and effective in preventing derailments, these systems only provide component defect information shortly before or even after failure has occurred. Consequently, these technologies result in thousands of main-line ISFs each year, during which a train must either stop on the main line for a component to be repaired or have a railcar set out at a nearby yard or siding. In addition, because of the short latency period between condition detection and failure occurrence, these systems must be installed at frequent intervals across the railroad network, resulting in high installation and maintenance costs. Because of the high cost and limited predictive ability of these reactive technologies, railroads have sought the development of railcar condition-monitoring systems.

Automated condition-monitoring technology (ACMT) includes wayside detection systems capable of monitoring the condition of railcar components over time in order to facilitate preventive maintenance. Examples of ACMT include wheel impact load detectors, truck performance detectors, acoustic bearing detectors, hot wheel

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**TABLE 1 Parameters for Single-Track RTC Simulations**

| Route Characteristic | Train Characteristic |
|---|---|
| 260 mi | Unit coal trains |
| 10 mi between control points | 115 cars, 6,325 ft long |
| 8,000-ft signaled sidings | 16,445 tons per train (loaded) |
| 2.5-mi signal spacing | 3,795 tons per train (empty) |
| Three-block, four-aspect signaling | 0.78 hp/trailing ton |
| 0% grade and curvature | Three SD70 4,300-hp locomotives |
| | Maximum speed: 50 mph |

intended as a guide to the methodology and to provide insights regarding the relative magnitude of the effects that might be expected in a route-specific analysis.

The simulated traffic consisted of 115-car unit coal trains on a 260-mi, single-track route. To replicate typical coal route operations, loaded trains were run in one direction along the route, while empty trains were run in the opposite direction. During the simulation, a train was stopped at random times on the main line in order to replicate 1-, 3-, and 5-h ISFs. Twenty-four simulations were performed using a random variation of train starts, with each train departing the terminal within ±15 min of its scheduled departure time. Total delay time was determined by subtracting the inherent delay for the base case (i.e., simulations without a service failure) from the delay for the simulations in which an ISF was initiated (Figure 1).

For each ISF length, average delay time increased exponentially with traffic volume. This exponential relationship is consistent with findings from other railway capacity research (*18, 19*). In addition, train delay curves increased more sharply for ISFs of greater length, indicating that main-line capacity on this route is more sensitive to longer ISFs.

Increases in train delay are mainly caused by increases in secondary delay. RTC simulations capture the shockwave effect created by an ISF, which is similar to those observed in highway traffic streams (*27*). Thus, a primary advantage of using RTC rather than a linear train delay cost calculator is the ability to more accurately predict delays to oncoming trains that are far away from the location of the ISF. In addition, RTC incorporates the time needed for braking and acceleration, thus providing more realistic train delay estimates.

## Dispatch Simulation Analysis: Double-Track Route

Since many of the corridors used to transport coal traffic experience high volumes and require a high level of maintenance, these routes are often built with multiple main-line tracks. As a result, RTC simulations were conducted using a double-track route. As before, 1-, 3-, and 5-h ISFs were randomly initiated to quantify total train delay at various traffic volumes. Twenty-two random simulations were conducted on the new route using the same train and route characteristics as before, except that the entire route contained two main-line tracks instead of a single track with sidings. During simulations, empty and loaded coal trains traveled in opposite directions, with each train type primarily using one specified track. As needed, trains were able to cross over to the other main-line track to run around stopped trains, following standard RTC dispatch simulation rules. Similar to the single-track simulations, train delay increased with an increase in either traffic volume or length of ISF (Figure 2).

As before, the increase in average delay is caused by increased secondary delay. Below a traffic volume of approximately 48 trains per day (i.e., one train on each main-line track per hour), average train delay increased linearly with traffic volume. However, above 48 trains per day, train delay increased exponentially.

In addition, variation in average delay times increased both at higher traffic volumes and for longer ISFs. A 95% confidence inter-

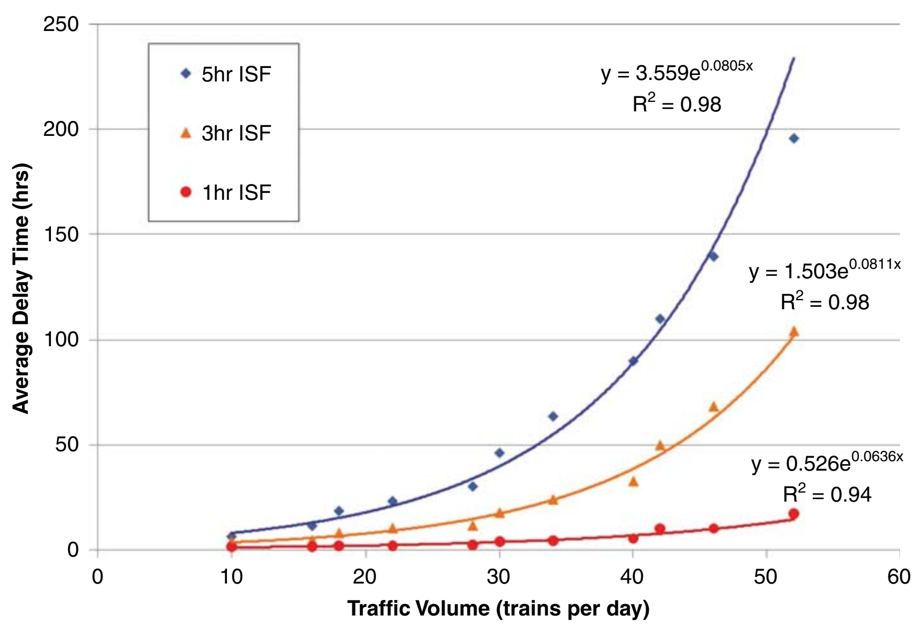



**FIGURE 1 Average train delay data generated from RTC dispatch simulation software for varying ISF durations on single-track route.**

detectors, cold wheel detectors, truck hunting detectors, wheel profile detectors, and machine vision. Detailed surveys of current wayside inspection technologies have been conducted by Lagnebäck (*8*), Steets and Tse (*9*), Bladon (*10*), Barke and Chiu (*11*), Robeda and Kalay (*12*), and Brickle et al. (*13*). The goal of ACMT is to facilitate condition-based maintenance, which is a "form of preventive maintenance based on vehicle performance and/or parameter monitoring" (*8*). Through the implementation of condition-based maintenance the physical condition of railcar components is monitored over time, allowing for trending analysis, early detection of deteriorating components, and the ability to predict component life. For example, through the use of acoustic bearing detectors, defective roller bearings can be identified much earlier than would have been possible with hot bearing detectors. By identifying railcar defects at an early stage and performing maintenance before component failure, railroads can reduce the likelihood of equipment-caused derailments and ISFs and take advantage of lower-cost, predictive maintenance strategies.

## LEAN RAILROADING

In 1990, the term "lean manufacturing" was introduced in a study at Massachusetts Institute of Technology (MIT). That study found Toyota's production techniques to be superior to their competitors' techniques in the automotive manufacturing industry (*14*). These findings helped to stimulate the use of lean methodology in other industries, and numerous companies throughout the world have since adopted lean methods. In the early 2000s, lean production techniques were formally applied to the North American railroad industry, although several key principles of lean railroading can be found in the earlier work of Sussman, Martland, and colleagues at MIT in the 1970s and 1980s (*15, 16*).

Lean is defined as the production of goods or services using minimal buffering costs (*17*). Sources of excessive buffering include both direct waste and variability. Direct waste is lean terminology for operations that are unnecessary. Examples in the railroad setting include accidents, ISFs, injuries, car damage, and unnecessary motion or information collection (*16*). Most managers focus on reducing these forms of direct waste, but another source of waste is variability.

Variability is a fundamental source of waste because it necessitates buffering in the form of extra inventory, capacity, or time (*17*). Common sources of excessive inventory buffering include variability in the frequency of ISFs caused by equipment, the length or severity of ISFs, and the level of maintenance required for various ISFs. These buffers can take the form of reserve supplies of empty or loaded freight cars and freight car components. Variability in train arrivals and unexpected defects requiring maintenance result in excess capacity buffers in railyards that may include extra yard tracks, car inspectors, or repair personnel. Finally, variability in run times, inspection and repair times, or labor availability may be buffered by adding slack time in the train schedule. All of these buffers are a result of the uncertainty inherent to various processes in the railroad system, and they lead to unnecessary costs in the form of indirect waste. Through the application of ACMT and condition-based maintenance, both the direct waste and the variability created by ISFs can be reduced.

ISFs result in both primary and secondary train delay. Primary, or exogenous delay, is direct delay caused by an external event affecting only the train experiencing an equipment defect (*18*). This includes either the time needed to repair a broken or defective railcar while on the main line or the time required to set out a car on a passing siding for future repair. Secondary delay, also called reactionary delay (*19*), is the delay to all other trains in the network affected by the service outage in some manner. According to lean principles, both primary and secondary delays that result from equipment-caused ISFs represent direct waste in the railroad network.

## ANALYSIS OF TRAIN DELAY

As U.S. freight traffic volumes have risen in recent years, research has been undertaken to better understand train delay and the impact of delay on network capacity and reliability. Schafer developed a train delay cost calculator to estimate the amount of train delay and the corresponding costs of broken rail-related derailments and service failures (*20*). In 2009, a study was conducted to understand the impact of higher train speed on freight railroad main-line capacity (*21*). More recent research has used Rail Traffic Controller (RTC) from Berkeley Simulation Software to analyze the impact of train type heterogeneity on railway capacity (*22, 23*). RTC is a dispatch simulation software package used throughout the North American railroad industry to simulate both freight and passenger operations (*24, 25*). Dingler provides an in-depth study of the use of RTC to investigate train delay and its relationship to capacity (*23*).

In the current study, RTC simulations were conducted on both single- and double-track routes, and the effect of train delay on unit coal traffic was analyzed. Results from these simulations were used to assess the potential economic impact of reducing equipment-related ISFs through the use of ACMT. In 2008, coal traffic comprised the greatest portion of tonnage and carloads originated (45% and 26%, respectively) and the most gross revenue (24%) among all commodities transported by U.S. Class I railroads (*26*). Additionally, unit coal trains operate on some of the highest-density rail corridors in North America, where delays caused by ISFs have the greatest impact. Another reason for analyzing unit coal traffic is the small variation in the design of railcars used to transport coal. This uniformity is advantageous for the design and implementation of machine vision and other condition-monitoring systems. For both of these reasons, the first applications for many ACMT systems will be unit train inspection on high-density coal routes.

### Dispatch Simulation Analysis: Single-Track Route

A common method of calculating train delay is through the use of dispatch simulation software, such as RTC. Previous rail capacity research using RTC provides a substantial background for the application of this software (*23*). A similar methodology was used in the current study, including the development of a representative North American single-track main-line subdivision and corresponding train schedule (Table 1).

The attributes used for this simulation were intentionally idealized for simplicity, as the purpose of this study was to determine the relative impacts of ISF length and traffic volume on main-line train delay. This analysis provides a baseline cost estimate for a typical rail route; however, estimation of costs for a particular route would require the actual characteristics specific to that route. Since route and traffic characteristics vary widely both among different railroads and within different subdivisions of an individual railroad, using actual characteristics would be highly specific, and results could not be universally applied. The analysis presented here is

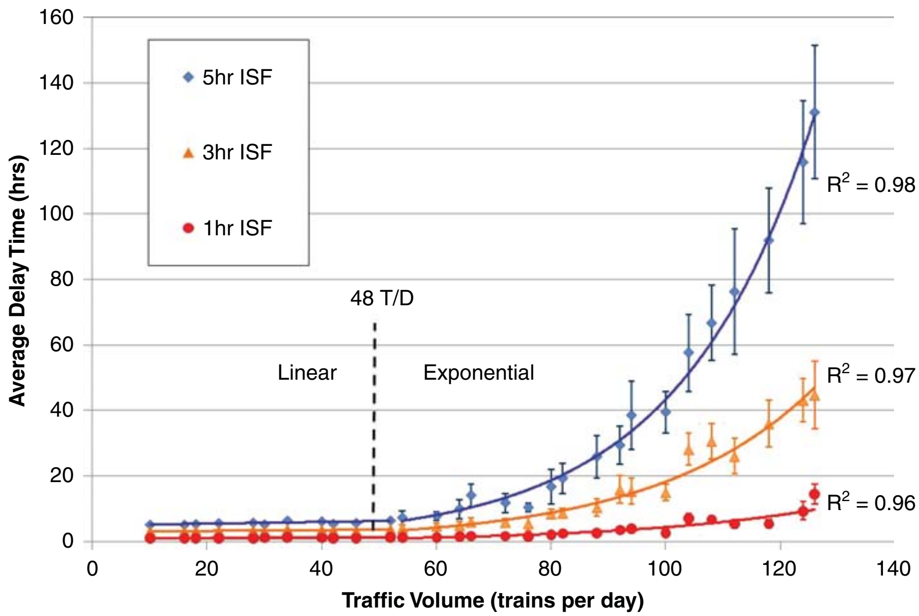



FIGURE 2 Total train delay as function of traffic volume with 95% confidence intervals for 1-, 3-, and 5-h ISFs on double-track route (T/D = trains per day).

val was used to determine the upper and lower bounds (denoted by the bars above and below each data point for average train delay in Figure 2). As traffic volume increased, the confidence intervals became larger, indicating an increase in variability. This variability in the system generates indirect waste that should be accounted for in addition to the direct waste created by train delay. An analysis of train delay variability is provided below.

## Estimation of Delay Cost for In-Service Failures

To determine the ISF-related delay cost incurred by a railroad, delay time is multiplied by a constant delay cost figure that includes four components: car cost, locomotive cost, fuel cost, and crew labor cost. The delay cost incorporates both the actual consumption of railroad company resources as well as the opportunity cost (in the case of cars and locomotives) of resources that are underutilized. A recent estimation of average total train delay cost was approximately $213 per train hour for U.S. Class I railroads (*20*). This figure assumes an average of 69.2 cars per train and 2.7 locomotives per train.

The present study assumed 115 cars and three locomotives per train. Accounting for these changes, the total train delay cost increased to $232 per train hour. This is assumed to be a conservative estimate, as it does not incorporate the lost revenue, or opportunity cost, caused by lading delay. Multiplying the constant hourly train delay value by average train delay times for various lengths of ISF resulted in cost curves following the same trends shown in Figure 1. Thus, for a 1-h ISF, the estimated total delay cost for the highest simulated traffic volume (52 trains per day) was approximately $4,150 (17.9 train hours × $232 per train hour). Assuming a 5-h ISF, as traffic volume increased from 20 trains per day (approximately 74 annual million gross tons [ANMGT]) to 52 trains per day (approximately 192 ANMGT), delay costs increased from approximately $5,000 to over $45,000.

In most cases, ISFs result in delays shorter than 5 h. In general, less severe ISFs result in one of two scenarios: (*a*) the train will be inspected and repaired along the line-of-road and will continue service after repairs have been made, or (*b*) the defective railcar(s) is removed from the train and set out at a nearby storage track, passing siding, or yard. For either case, industry surveys estimate that the train will typically be delayed between 1 and 2 h. Using an approximation of 1.5 h, the potential costs of different types of ISFs at various traffic levels can be estimated as low (10 trains per day, or 37 ANMGT), medium (25 trains per day, or 92 ANMGT), and high (40 trains per day, or 148 ANMGT). According to RTC simulation data, a 1.5-h ISF will result in delay costs of approximately $460, $980, and $2,850 for low-, medium-, and high-traffic routes, respectively.

## Cost Estimation Using Both Single- and Double-Track Routes

Main-line capacity is directly related to the physical infrastructure along a fixed route length. Increasing the number of tracks on a line (e.g., upgrading from single track to double track) results in a disproportionately greater increase in capacity (*18*). As a result, for traffic volumes under 48 trains per day (approximately 177 ANMGT), the delay costs caused by ISFs on a double-track route were almost negligible compared with those on a single-track route (Figure 3). The delay costs at these volumes were all less than $1,500 regardless of ISF length. Although not shown in Figure 3, these costs displayed a linear trend, as seen with the delay time data (Figure 2).

A survey of U.S. Class I railroads indicated that they experience over 23,000 equipment-caused ISFs per year. These include ISFs caused by failed freight car components as well as those that occur in response to reactive wayside detectors, including hot bearing detectors and wheel impact load detectors. Total delay costs were

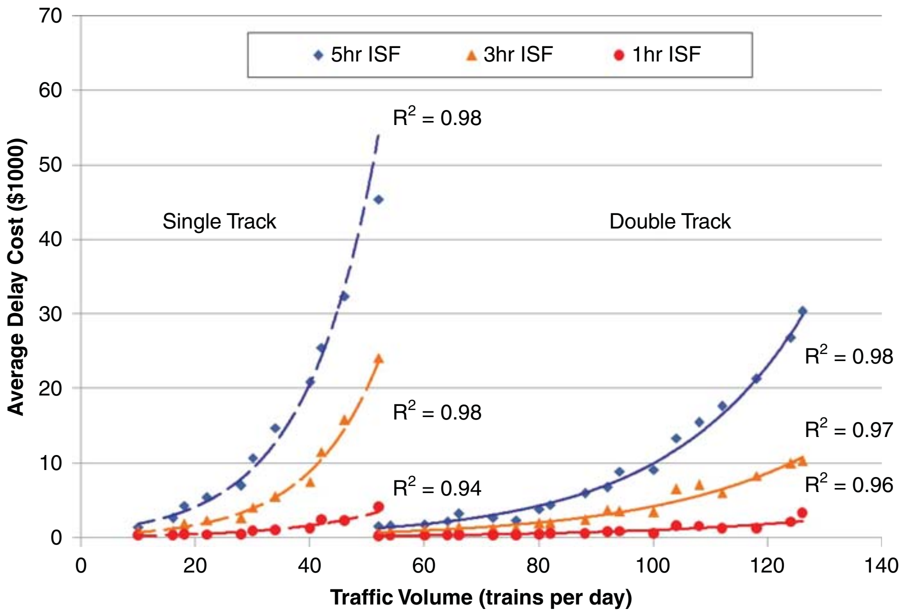



**FIGURE 3 Total train delay as function of traffic volume for 1-, 3-, and 5-h ISFs on single- and double-track routes.**

calculated on the basis of these numbers by using delay cost estimates for a sample 1.5-h ISF for different track types with average traffic volumes on the U.S. railroad network (Table 2).

Averages for the percentage of ton-miles on various single- and double-track routes were determined by using data from the *National Transportation Atlas* of the Bureau of Transportation Statistics (*28*). Although these ton-mile percentages include other types of traffic besides unit coal trains, final cost estimates should still be conservative because lading delay costs for other commodities will generally be higher. These data indicate that approximately 1% of U.S. ton-miles are transported on routes with more than two main tracks, but since delay costs would be minimal, these routes were not included. Multiplying delay costs by ton-mile percentages at each level of traffic, the annual failure cost is approximately $15.2 million per year for U.S. class I railroads. For comparison, the average annual cost of track and equipment damages caused by main-line derailments was approximately $35 million for the four largest U.S. Class I railroads from 1999 to 2008 (*2, 29*). Thus, delay costs caused by main-line delay from ISFs appear to be substantial compared with the costs associated with derailments.

By identifying the costs associated with equipment-caused ISFs, railroads can more accurately assess the value of ACMT installation. Improved understanding of the cost benefits of ACMT can allow railroads to make better decisions regarding their technology implementation strategies. For example, since ISFs create much more train delay on single-track than double-track routes, railroads may choose to install a greater proportion of their ACMT in regions with large amounts of single track. However, it should not be assumed that increased implementation of ACMT will immediately result in proportionate reductions in equipment-caused derailments or ISFs. In some cases, new ACMT installations could initially result in additional ISFs caused by false alarms. However, as these technologies are further tested and improved, appropriate component inspection thresholds will be determined, and system accuracies will increase. A key area of future research will be the development of a condition-monitoring efficiency metric to assess the proportion of equipment-caused failure costs that can be recovered using ACMT.

**TABLE 2 Train Delay Cost and Percentage of Ton-Miles by Track Type Based on RTC Simulation Data for 1.5-h ISF with Various Traffic Volumes (*28*)**

| | Single Track | | Double Track | |
|---|---|---|---|---|
| Average ANMGT | Delay Cost ($) | Ton-Miles (%) | Delay Cost ($) | Ton-Miles (%) |
| <40 (~37) | 460 | 31.3 | 350 | 0.9 |
| 40–60 | 590 | 17.9 | 350 | 2.3 |
| 60–100 | 1,000 | 18.7 | 360 | 6.2 |
| >100 (~110) | 2,170 | 5.5 | 440 | 16.3 |
| Total | 556.45[a] | 73.5 | 104.83[a] | 25.6 |

[a]Weight average based on percentage of ton-miles.

## VARIABILITY IN TRAIN DELAY

Because variability results in necessary buffering (e.g., added slack time in train schedules), it is a fundamental source of waste (*16*). RTC simulations indicated that the variability associated with equipment-related main-line train delay increased both with traffic volume and ISF length. Both factors were analyzed separately by using frequency diagrams with the number of trains delayed versus the length of individual train delay (in minutes) per 100 train miles. The lengths of individual train delays were divided into 10 individual frequency bins. These frequency bins ranged from 0 to over 270 min for the single-track route and from 0 to 90 min for the double-track route.

Trains in the first bin experienced little or no delay, while the trains in the last bin incurred the largest amounts of delay. Curves showing the percentage of total trains are also provided to more clearly illustrate the increased variability.

## Length of In-Service Failure and Variability

The first factor analyzed was the length of ISF. To best evaluate the impact of this factor, simulations using the single-track route were chosen at the highest simulated traffic volume (52 trains per day, or 192 ANMGT). Although this traffic volume is higher than that of most single-track operations, using exaggerated conditions in the simulations highlights the impact of ISF length on main-line capacity, allowing qualitative analysis of this factor. In the previous sections, total delay was calculated by subtracting the delay for the base case from the delay for 1-, 3-, and 5-h ISFs. In this analysis, the frequency of delay for ISFs was compared with the base case (0-h ISF) to show changes in train delay variability. Therefore, train delay for this analysis was defined as the difference between the minimum, or unopposed, run time and the actual time it takes a train to traverse the route (*22*). Given this definition, over 60% of the trains in the base case experienced between 30 and 60 min of delay (Figure 4).

As the length of ISF increased from 0 to 5 h, both average train delay and train delay variability increased. For the various ISF lengths, the distribution of the data shifted from a skewed distribution to one that was more symmetrical, with the modal value increasing (i.e., shifting to the right) as the length of delay increased. For the base case, most trains experienced 30 to 60 min of delay (per 100 train miles), while for a 5-h ISF, the modal value was 120 to 150 min. The distribution curves became wider and shorter for longer ISFs, indicating an increase in variance. This increase in variance affects a railroad's level of service, because when a higher percentage of trains is delayed, more customers are affected, resulting in greater costs to the railroad.

For double-track routes, the increases in average delay and variability were not as evident. The double-track route described above was analyzed using the highest simulated traffic volume (126 trains per day, or 465 ANMGT). Since there is less total delay on the double-track route, 10-min frequency bins were used instead of the 30-min bins shown in Figure 4. The data show that for a 1-h ISF, 90% of the trains experienced little or no effect (i.e., 0 to 10 min of delay), and none of the trains were delayed for more than 30 min (Figure 5*a*). However, for a 5-h ISF, only 46% of the trains experienced little or no effect, and over 25% of the trains experienced a delay greater than 30 min. As expected, the longer the ISF, the greater the number of trains affected.

The distribution of the frequency bars provides information about the variance of the train delays. To more clearly see these distributions, the data are displayed for only the delays greater than 10 min (Figure 5*b*). For 1- and 3-h ISFs, the frequency of delays decreased as the length of delay increased. However, the 5-h ISF case followed a different trend. Unlike the other distributions, the distribution of the 5-h ISF increased at the highest levels of individual train delay. These data suggest that when a service outage exceeds a certain threshold, the shockwave affecting the network becomes larger and more unpredictable. Thus, although the effects were not as pronounced as in the single-track route, the length of service outage affected the amount of operational waste generated in the network.

## Traffic Volume and Variability

For the second factor, traffic volume, data were analyzed for a 5-h ISF on both the single- and double-track routes with traffic volumes set from 16 to 52 and 64 to 126 trains per day, respectively (Figures 6 and 7). Similar to the impact of ISF length, increased traffic volume resulted in increased variability in train delay. As before, the distribution curves for the single-track data shifted to the right and became wider and shorter as traffic volume increased (Figure 6).

The impact of traffic volume on train delay was less apparent on double-track routes because of the much greater line capacity (Figure 7). However, it is clear that average train delay and train delay variability increased at higher traffic volumes. For very high traffic volumes (i.e., above 82 trains per day, or 302 ANMGT), the train frequency distributions were not normally distributed (Figure 7*b*). Instead, the number of trains delayed decreased until the length of individual train delay reached approximately 70 min and then began

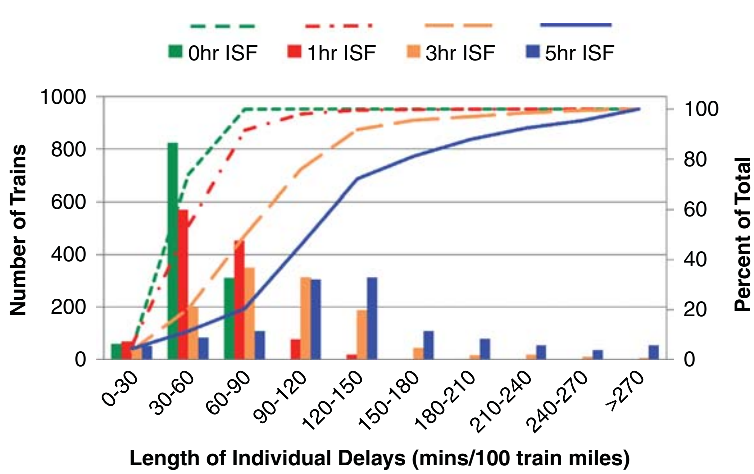
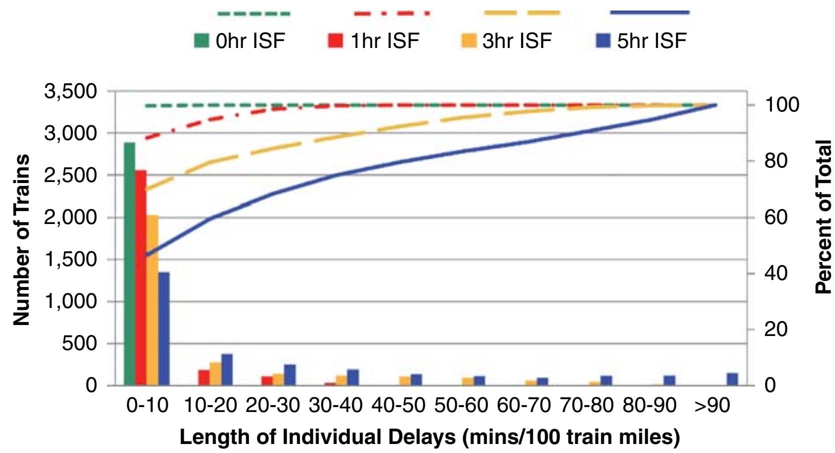
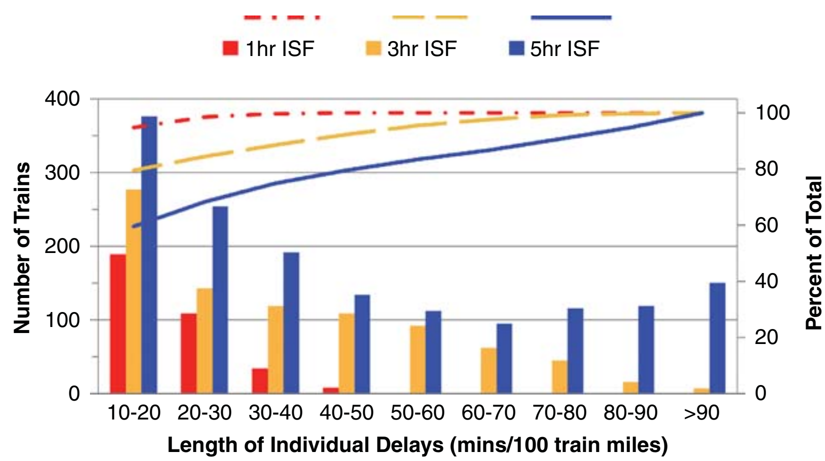



FIGURE 4 Frequency diagram showing amount of delay for each train caused by various ISFs on single-track route with 52 trains per day.




(a)




(b)

FIGURE 5 Frequency diagrams showing amount of delay caused by various ISFs on double-track route with 126 trains per day for (*a*) each train and (*b*) trains experiencing delays longer than 10 min.

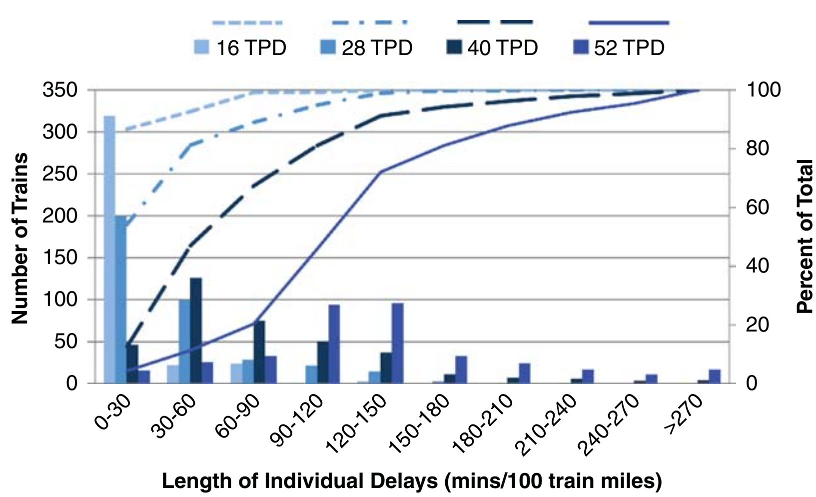
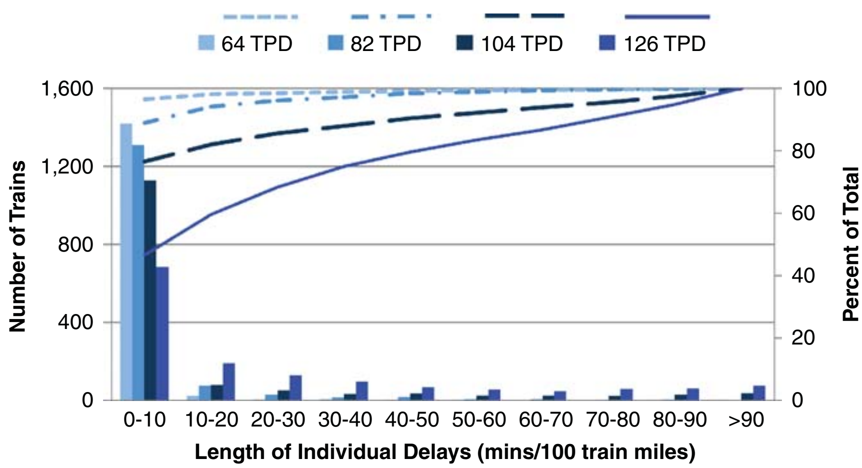
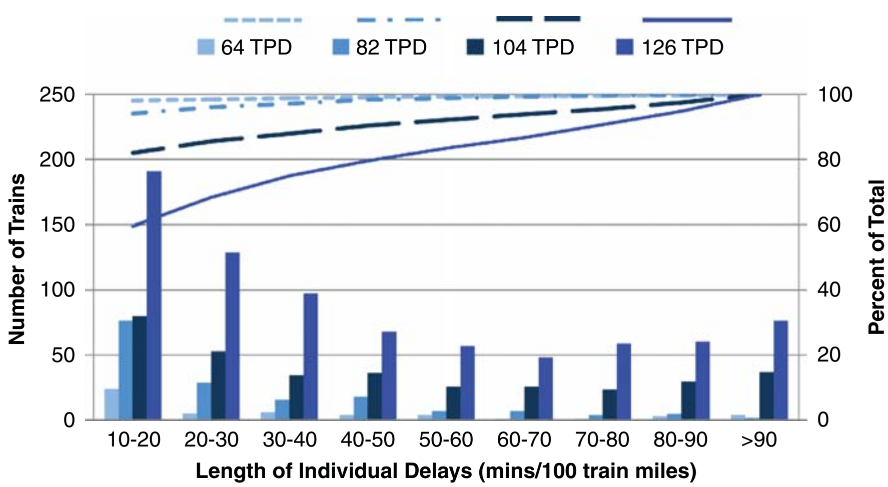



FIGURE 6 Frequency diagram showing amount of delay for each train caused by 5-h ISF on single-track route with varying traffic volumes (TPD = trains per day).




(a)




(b)

FIGURE 7 Frequency diagrams showing amount of train delay caused by 5-h ISF on double-track route with varying traffic volumes for (*a*) each train and (*b*) trains experiencing delays longer than 10 min.

to increase. In other words, the mechanical reliability of freight cars becomes more important at higher traffic levels. Although this is true for double-track routes, its impact is much greater on single-track routes.

## CONCLUSIONS

The effectiveness of railcar condition monitoring has a large impact on rail transportation efficiency. Dispatch simulation software was used to analyze the effect of ISF duration and traffic volume on single- and double-track versions of a hypothetical route to estimate train delay. The simulations indicated that both traffic volume and ISF length had a nonlinear effect on delay, with traffic volume having an exponential effect. The associated costs may be higher than previously estimated, especially for high traffic volumes. Based on RTC simulation data, the estimated cost of the direct waste caused by these main-line delays is approximately $15.2 million per year for U.S. Class I railroads. Although train delay costs caused by ISFs are not often considered in economic analyses of ACMT systems, they are substantial compared with the track and equipment damages associated with derailments. Another factor not often considered is the large variability in train delay at high traffic volumes. When variability increases, there is a higher probability that more trains will experience longer delays, resulting in indirect waste in the form of increased time buffers. Although the costs caused by variability are more difficult to quantify, this negatively affects the level of service that railroads can offer their customers. Additional failure costs associated with train delay can be recovered by improving railcar inspection and maintenance practices and reducing the likelihood of equipment-caused main-line ISFs. These costs are considered in more detail by Schlake, who provides a thorough study of the impact of ACMT on freight railroad safety and efficiency (*30*).

## FURTHER RESEARCH

The present study developed a framework to assess the potential impact of equipment-related ISFs on railroad main-line efficiency. In order to determine the total costs and benefits of implementing

ACMT, a metric should be developed to determine the effectiveness with which critical railcar components can be monitored. This metric would be a function of both the accuracy of ACMT systems and the statistical probability that a specific railcar defect would cause an ISF. In order to develop this metric, appropriate data must be collected and analyzed from field installations of ACMT and from records of ISF occurrences. These analyses would allow the proportion of ISF costs that could be recovered using ACMT to be determined. In addition, by determining the most critical railcar components (i.e., those that are most likely to cause an ISF or derailment), automated inspection efforts could be directed most effectively to prevent the maximum number of ISFs and reduce the variability in their duration. Once this metric is developed for unit coal train operations, these methods could also be applied to other traffic types, such as intermodal operations.

Findings from this study indicate that ISFs have a much greater impact on single-track than on double-track operations. Both train delay costs and delay variability were higher for single-track routes. As a result, an important area of future research is determining optimal locations for ACMT installations while taking the cost of ISF-caused main-line delays into account. Ouyang et al. found that simply installing ACMT at the busiest locations on a network yielded suboptimal results (*31*). However, it may be beneficial to develop additional optimization models aimed at minimizing the cost of main-line train delay. This would allow railroads to not only ensure full coverage of their railcar fleets by ACMT, but also provide the capability to prevent equipment-caused ISFs in areas of particularly high traffic or limited capacity.

Other technologies may also provide additional means of reducing equipment-caused ISFs. Technologies capable of performing onboard diagnostics for railcar components could result in substantial reductions in train delays. Electronically controlled pneumatic brakes are a prime example of this type of technology. As with ACMT, a metric could be developed to determine the proportion of equipment-caused ISFs that could be reduced through the use of electronically controlled pneumatic brakes. Although it is not likely that the reduction in main-line train delays would justify the cost of retrofitting a fleet of cars with electronically controlled pneumatic brakes, this is a factor that should be considered in cost–benefit analyses for this technology.

Another area of future research is the quantification of train delay costs associated with major derailments. For longer main-line service outages (e.g., 24 to 48 h), in the present study performing RTC simulations was impractical because of the amount of time and computational resources required. In addition, because of the rerouting that occurs and other complexities that accompany derailments, actual train delay costs cannot be easily estimated using either linear or exponential estimation methods. Since these costs would vary substantially among different routes, the best approach may be to use empirical analysis with historical derailment data.

Finally, future research should assess the costs associated with ACMT implementation, including purchase and installation, system maintenance, electronic infrastructure, integration (including the time and expense of incorporating institutional changes), and additional railcar maintenance resulting from improved inspection effectiveness. A thorough analysis of both the costs and benefits of improved railcar condition monitoring will provide railroad management with the tools necessary to make informed decisions regarding the implementation of ACMT.

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