

Reducing Network Costs Through Improved Vehicle Maintenance: A Lean Production Approach

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Abstract

Railroad yard throughput and terminal performance directly impact overall network capacity. An important element affecting terminal performance is the efficiency at which railcars are inspected and repaired. Technologies are being developed to automate railcar inspections that have the potential to improve railroad terminal efficiency as a result of reduced inspection times and improved rail terminal operations. This research applies Lean Manufacturing methods to the railcar maintenance process and investigates potential means of eliminating waste and reducing variability through the implementation of automated condition monitoring technologies. We consider the potential impact on intermediate 1,000-mile unit-train inspections and quantify the direct and indirect delay costs resulting from railcar inspection. This analysis provides a basis for developing cost-effective inspection and maintenance strategies using automated technologies and evaluates potential benefits in terms of improved efficiency and increased capacity.

1.0 Introduction

Railcar inspection and maintenance practices in the United States have evolved substantially in the past century. In the early years of US rail transportation, inspection technology included a hammer to “sound out” cracked or broken wheels, a piece of chalk or other marking device to identify cars with possible defects, and a lantern for inspecting trains at night (1, 2). Under these practices, the safety and reliability of a railroad’s rolling stock was heavily dependant on the mental acuity, physical ability, and training of its car inspectors. These practices continued until the latter half of the 20th century, when various technologies were developed to more effectively detect railcar equipment defects. Over the past several decades, US Class I railroads have made considerable investment in the development and implementation of these technologies. The benefits of reducing equipment-related derailments and in-service failures provided sufficient economic justification for capital investment in these systems (3). In addition, these technologies have the potential to improve yard efficiency through enhanced planned maintenance practices and reduced inspection redundancy as compared to the current system. In the current era of limited network capacity and greater demands for reliable service, improvements in yard and terminal efficiency will become increasingly important. This paper reviews and assesses the current state of railcar inspection in the context of terminal operations, and projects potential benefits associated with automated condition monitoring and improved maintenance strategies.

2.0 MOTIVATION AND BACKGROUND

As early as 1925, the railway terminal was identified to be a major source of lost productivity in freight operations (4). By the 1960s, terminal efficiency had become a major focus in railroad engineering research (5). As railway terminal research continued during the latter half of the 20th century, management techniques were also evolving in other industries to improve production and manufacturing efficiency. In the 2000s, various production management techniques were applied to terminal operations through the introduction of Lean Railroading (6, 7). Lean Railroading provides a

means of eliminating operational waste by improving the overall capacity, efficiency and asset utilization of a railroad terminal. As railroads continue to take advantage of newly available technologies and management strategies, principles from Lean Railroading can be applied to individual aspects of terminal operations, including railcar inspection and maintenance practices to further improve efficiency.

2.1 Terminal Performance

In the current railroad environment, yards and terminals have a sizeable impact on both productivity and reliability. In regards to general manifest traffic, Murray states that, "Cars spend most of their time in terminals, and that's where the service battle is won or lost for carload business" (8). Dirnberger cites several reports stating that as much as 64% of railcar transit time is spent in yards (6, 7). A common metric used to describe this time spent in yards is terminal dwell, which is measured in hours and is defined as the average time a car resides at a specified terminal location (9). Dirnberger noted the relationship between terminal dwell and train velocity, concluding that average train speed decreases linearly with increased terminal dwell (6, 7). Average train speed, calculated by dividing train-miles by the total hours of train operation (9), is often used as a proxy for railroad performance. An estimation by Logan suggested that for every 15% reduction in systemwide average terminal dwell, there would be an increase of 2 mph in the average train speed for carload traffic (6, 10). In May 2010, US Class I railroads had an average train speed of approximately 25 mph and a systemwide average terminal dwell of approximately 22.5 hours (9). Although the exact relationship between terminal dwell and train speed varies among different railroads, reducing the former will almost always lead to an increase in the latter.

2.2 Lean Railroading

The concept of Lean Railroading was developed throughout the 2000s as an approach to improve efficiency in classification yards. According to Dirnberger, "Because classification terminals can be considered production systems, their performance can be improved by adapting an integrated approach consisting of three proven production management techniques: lean, theory of constraints (TOC), and statistical process control (SPC or Six Sigma)" (6, 7). In this analysis, we will focus only on the concept of lean production, as it has been applied to railroad terminal operations, in the form of Lean Railroading.

In 1990, the term "Lean Manufacturing" was first introduced in a study at Massachusetts Institute of Technology (MIT). That study concluded that Toyota production techniques were superior to other competitors in the automotive manufacturing industry (11). These findings helped launch the use of lean methodology and other principles, first implemented by Toyota, that have been adopted by numerous companies throughout the world (12). Although similar principles had been previously used in railroad terminals, the first formal application of lean techniques occurred in the early 2000s by Dirnberger and the Canadian Pacific Railway (CPR) Yard Operations Performance Group.

Lean is defined as the production of goods or services using minimal buffering costs (13). Sources of excessive buffering include both direct waste and variability. Direct waste is lean terminology for operations that are not needed. Examples in the rail yard setting include: rework, accidents, injuries, car damage, unnecessary motion, and unnecessary information collection (7). Most managers focus on the reduction of direct waste, but spend less effort on reducing variability. Variability, however, is a fundamental source of waste, as it necessitates buffering in the form of extra inventory, capacity, or time (13). In the rail yard, sources of excessive inventory buffering include variability in: fueling requirements, the number of railcars or locomotives requiring maintenance, and the extent of the maintenance required. These buffers can come in the form of reserve supplies of diesel fuel, freight car components, locomotive parts, etc. Variability in train arrivals and unexpected defects requiring maintenance result in excess capacity buffers, which may include extra yard tracks, car inspectors, or repair personnel. Finally, variability in arrival 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 the various processes within the rail yard, and they lead to unnecessary costs in the form of indirect waste.

Adapting work from Hopp and Spearman (13), Dirnberger developed steps for implementing Lean Railroading in terminals (6). These steps included: eliminating direct waste, swapping buffers, reducing variability, and performing continuous improvement. Applying a version of Lean Railroading in their yards, CPR saw dramatic improvements over a one-year period: average terminal dwell dropped by over 28%, average terminal capacity increased by 40%, and average train speed increased 3.6 mph (6). Several other railroads and railroad suppliers including Union Pacific (UP),

BNSF, Norfolk Southern (NS), Belt Railway of Chicago (BRC), and General Electric Yard Solutions are now applying aspects of Lean Railroading to improve terminal performance (7). As railroads continually seek to improve terminal performance, new methods and technologies will be integrated into the yard system to further eliminate waste and reduce variability. Improving railcar inspection and maintenance practices is one avenue for integrating lean processes with railroad terminal operations.

Autonomation and Inspection

The Toyota Production System that first popularized the concept of just-in-time (JIT) production was a predecessor to the concept of lean production (11). In addition to JIT, a major element of the Toyota Production System is autonomation, or “automation with a human touch” (13, 14). In the same way that lean techniques have been applied to rail terminal operations in a broader sense, the principles of autonomation can be applied to railcar inspection and maintenance practices to improve terminal performance. As stated above, a railroad terminal can be viewed as an industrial production system. If the product being “manufactured” is efficient, safe, and reliable transportation provided by trains, then the train inspection process can be likened to a form of quality control. In many industrial settings, quality control requires visual inspection, which can take on several forms including manual inspection, automated inspection, or a hybridization of the two (Table 1).

TABLE 1. Comparison of various inspection systems (adapted from Hou et al. 1993) (15)

System	Search	Decision	Remarks
Pure human inspection	H	H	Time consuming, but effective
Computer-search human decision	C	H	Efficient and effective, applicable to newer technologies
Human-computer decision-making	C	H + C	Efficient and effective, for well-established technologies
Pure automated inspection	C	C	Efficient but subject to false alarms

H = Human, C = Computer

Models of humans and machines have been used to derive hybrid automation, which typically performs better than either human or machines alone (15, 16). In general, machines are faster at performing defect detection (search) functions, while humans are better at making decisions regarding the validity and/or severity of defects (15). In some cases, machines can be useful in aiding a human in those decisions. For example, a computer-vision system could highlight a location within a digital image where a defect may be present, and the human operator would decide whether or not the highlighted section actually contains a defect. Railcar inspection systems with well-established detection mechanisms (e.g. WILDs or ABDs) could be programmed so that a computer performs the decision function when the likelihood of a defect is high (e.g. a wheel impact load of over 100,000 lbs.), but the decision is deferred to a human inspector when the defect likelihood is lower (e.g. a wheel impact under 80,000 lbs).

In other cases such as machine vision technology, the machine may not always be capable of making accurate decisions, so a computer-search human decision system would be most appropriate. For example, a machine vision system may identify a line of mud or dirt as a possible cracked center sill. The system could flag this car, highlight the location in question, and allow the car inspector to visually inspect the center sill and confirm or reject the computer’s suggestion. Regardless of the system arrangement, these technologies would eliminate wasted effort and allow car inspectors to focus their attention on the cars that are most likely to have component defects.

2.4 Current Railcar Inspection Practices

United States Department of Transportation (US DOT) Federal Railroad Administration (FRA) regulations require that every car placed in the train must receive a mechanical inspection before the train departs from a yard or terminal (17). In addition, trains travelling long distances must be stopped for inspection after 1,000 miles, but are allowed to travel up to 3,500 miles between inspections if special conditions are met. When a train is initially inspected after being assembled in a classification yard or terminal, the inspection is referred to as an initial terminal, or Class I inspection, whereas 1,000-mile intermediate inspections are referred to as Class IA inspections. To meet the FRA requirements for Class I and Class IA inspections, railroads must rely heavily on the manual

inspection of freight cars. Current railcar inspection practices require a car inspector, referred to as a carmen, to walk or ride a vehicle along the entire length of a train, visually inspecting the mechanical components on both sides of each car. These inspections can vary in their efficiency and effectiveness depending on the particular experience or ability of the car inspector. As a result of the inherent inefficiencies and subjectivity of manual inspection, railroads have developed technologies to augment the efforts of human car inspectors.

2.5 Automated Condition Monitoring Technology (ACMT)

Since the early 1990s the US railroad industry has invested over \$70 million on the development, installation and maintenance of wayside detection systems capable of monitoring the condition of freight car components (3). Referred to in this paper as automated condition monitoring technology (ACMT), These systems use various sensing mechanisms to measure heat, force, sound, and visual parameters in order to monitor the condition of railcar components. Earlier wayside detection systems were designed to identify defective components en-route in order to prevent derailments caused by overheated journal bearings, dragging equipment, or other defects. These inspection systems are essential for preventing derailments, but because of their reactive approach to defect detection, they do not greatly improved the efficiency with which maintenance is performed. However, new detection systems in the form of ACMT have the capability to facilitate preventive maintenance through accurate and objective condition monitoring.

Condition monitoring of railcar components is conducted over time to allow for trending analysis and early detection of deteriorating components. For example, technologies such as acoustic bearing detectors (ABDs) and truck performance detectors (TPDs) are now providing mechanical department management with pertinent information to facilitate the removal of faulty journal bearings or truck components prior to failure. Other wayside detection systems capable of condition monitoring include wheel impact load detectors (WILDs), hot wheel detectors (HWDs), cold wheel detectors (CWDs), truck hunting detectors (THDs), and wheel profile monitoring (WPM) systems. Several detailed surveys of current wayside inspection technologies have been performed including Steets and Tse (1998), Bladon et al. (2004), Barke and Chiu (2005), Robeda and Kalay (2008), and Brickle et al. (2008) (18, 19, 20, 21, 22). In addition, an analysis was performed in 2009, which validated the economic viability of researching, developing, and implementing ACMT (3).

North American railroads are interested in earning high returns on their capital investments, including investments in emerging technologies for railcar inspection and condition monitoring. While immediate returns will be found through the reduction of equipment-caused derailments and in-service failures, longer-term benefits may be realized through improved yard efficiency and increased asset utilization. By implementing Lean Railroading principles, decisions can be made regarding railcar inspection and maintenance that can improve yard efficiency and provide systemwide economic benefits.

3.0 METHODOLOGY: APPLYING LEAN TO RAILCAR INSPECTION

Using the four step process developed by Dimberger (6), the following Lean Railroading principles were applied to railcar inspection and maintenance practices: eliminate direct waste, swap buffers, reduce variability, and perform continuous improvement. Data from a major US Class I railroad terminal were used to assess the potential benefits of using ACMT in conjunction with lean techniques.

3.1 Eliminate Direct Waste

The main goal of any lean production system is to convert waste into value. The first step in eliminating waste is to separate the value-adding operations in the system from the non-value adding operations. Actions that create no value but are unavoidable with current technologies are considered Type I waste, whereas steps that create no value and can be immediately avoided are considered Type II waste (12). In this case study of railcar inspection processes, both Type I and Type II waste will be considered.

3.1.1. Type I Waste: Inherent but Unavoidable Waste

One example of Type I waste inherent to railcar inspection is the tagging of bad order cars. Each time a car inspector identifies a railcar in need of major repair, a bad order card must be completed and affixed to each side of the railcar. The tagging of bad order cards creates Type I waste because there is currently no available technology designed to automate this process, thus it must be performed manually. Data from empty coal train inspections in one major US Class I railroad terminal

indicate a linear increase of approximately 9.9 minutes (0.166 hrs) in total inspection time for every additional bad order identified by the car inspectors (Figure 1).

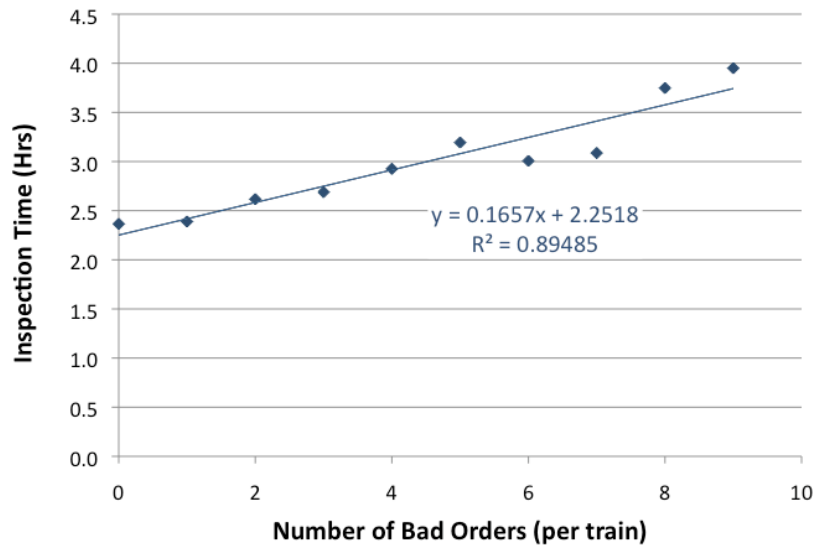


FIGURE 1. Average coal train inspection times as a function of the number of bad orders found per train

These data suggest that it takes car inspectors approximately 10 minutes to perform the following tasks: 1) identify an FRA-reportable defect, 2) complete required documentation on the bad order cards, and 3) attach one bad order card to each side of the defective railcar. By lean production standards, steps 2 and 3 are considered Type I waste, because this process does not improve the train's condition, and if the appropriate technology and procedures were in place, the time needed for this process could be greatly reduced.

Nationwide, hundreds of thousands of freight cars are bad ordered each year. Therefore, assuming new technology could reduce the time needed to document a bad order, the railroad industry could substantially reduced Type I waste in railroad terminals. This could be accomplished by linking wayside detection systems and automatic equipment identification (AEI) data with handheld devices in the yard, allowing car inspectors to electronically bad order cars. Innovations such as this would improve productivity through the elimination of wasted effort.

3.1.2 Type II Waste: Immediately Avoidable Waste

An inspection process, by definition, does not add value to the customer and therefore generates operational waste. In many industries, product inspection (i.e. quality control) is a necessary requirement due to imperfections in the manufacturing system. In the yard production system, the products (outbound trains equipped with the necessary resources to travel safely and reliably to their next destination) are made of many reusable parts (locomotives and railcars), some of which contain defects with varying levels of severity. Railcar inspection, in and of itself, does not add value to the product, but rather allows the opportunity for value to be added through car repair and more reliable, efficient train operation. After inspecting an entire train, a car inspector has not added value to that train unless he or she has made a repair or in some other way improved the condition of at least one railcar in the train. For this reason, a primary industry goal for improving railcar maintenance practices is to "turn finders into fixers" (23). ACMT can be used to find defects so railroad personnel can spend their time adding value to the product.

A specific example of Type II waste is the unnecessary redundancy that occurs when railcars are inspected too often. Under current industry practices, non-defective railcars are regularly inspected numerous times between origin and destination. In general, there is no system in place to record the results of these inspections. This process is redundant, inefficient and suboptimal in terms of achieving the actual goal of finding and repairing defects before they cause a problem. Inspectors have no way to know with any certainty if a particular component was found to be in satisfactory condition at the previous inspection point. Consequently, they must expend time inspecting all

components, regardless of their actual condition. This process is repeated over and over again with the result that some components that are quickly inspected are over-monitored. Meanwhile, components or conditions on the railcar that are difficult to assess may not be carefully or frequently observed. This result is a direct outcome of adherence to the current regulations that emphasize inspection frequency, not efficient detection and repair of defects.

Recently, there have been efforts to reduce the time car inspectors spend inspecting healthy (non-defective) railcars. In 2008 the FRA amended the regulations pertaining to freight equipment to allow trains equipped with electronically controlled pneumatic (ECP) brakes to travel up to 3,500 miles before stopping for an air-brake inspection (17). Through the implementation of ECP brakes, railroads can reduce Type II waste and immediately recover the labor costs associated with excessive car inspections, while at the same time achieve the associated safety benefits.

Data collected at one Class I railroad terminal indicate that manual Class IA inspections take between 80 and 140 minutes (1.33 to 2.33 hours) per train, depending on train type (Figure 2). Train inspection procedures on most Class I railroads use two car inspectors per train, one on each side of the train. As a result, a 140-minute coal train inspection requires 4.66 person-hours of labor. These inspection times are generally consistent with observations at other Class I railroad terminals.

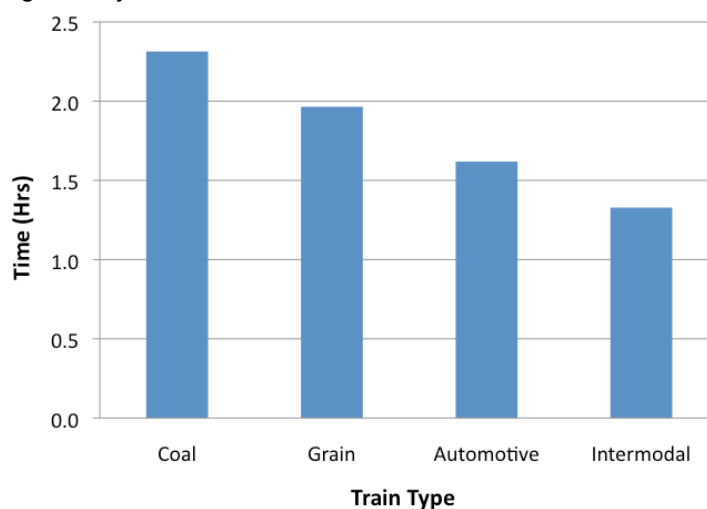


FIGURE 2. Average train inspection times for various train types

Differences in inspection times are likely a result of differences in train length and the priorities placed on different train types, with intermodal trains having the highest priority. Since most inspections require one car inspector to be positioned on each side of the train, this results in 2.67 to 4.67 person-hours of labor per train. Since most trains contain only a few cars with component defects, the majority of this time involves inspecting cars that have none. Therefore, by equipping trains with ECP brakes, railroads could run unit trains 3.5 times farther between inspections than they currently can, resulting in the elimination of one or two Class IA inspections per long-haul train. The reduction in Type II waste alone would not be enough to justify the cost of retrofitting an entire train with ECP brakes; however, this is a major factor that should be considered when assessing the potential benefits of ECP brakes. Furthermore, as ACMT continues to develop and more systems are validated for accuracy, additional regulatory relief may be offered by the FRA. This would allow for longer distances between Class IA inspections on routes containing a sufficient number of wayside condition monitoring sites.

3.2 Swap Buffers

To improve efficiency, buffers can be swapped to eliminate indirect waste. According to lean methodology, for a given set of resources, when one buffer is reduced, another buffer must be increased. A common practice of Lean Railroading is to decrease the time buffer (dwell time) by increasing either the inventory or capacity buffer (7). One example of how buffers can be swapped as a result of ACMT is by shifting mechanical personnel from inspection tasks to repair activities. As ACMT is used to augment manual railcar inspections, less labor will be required to perform the same number of inspections. As a result, railroad managers can shift personnel from the inspection yard to the repair facility, reducing the time buffer and increasing the capacity buffer. This increase in the capacity buffer would potentially allow more cars to be repaired. In this way, waste can be eliminated

and value added to the system through car repair. However, there may be factors that limit the extent to which the capacity buffer can be increased such as the size of the repair facility or the number of available repair tracks. As a result, railroads must incorporate a broad, system-wide view of all relevant processes before appropriate buffers can be determined.

3.3 Reduce Variability

Variability is a subtle but important source of waste. By reducing system variability, tasks can become more autonomous and buffers can be reduced. The maintenance of railcars is subject to considerable variability because bad orders of varying degrees of severity are often encountered and must be addressed. This variability can lead to waste because resources, including replacement parts and labor, are limited. For example, if there are only a few bad orders during the course of one week, the extra parts remain unused and repair personnel sit idle. Conversely, if there are more bad orders than usual, there may not be enough repair personnel to perform all the work, they may run out of replacement parts, and there may not be enough capacity for the cars to be accommodated in the repair facility. Thus, variability in the car inspection process leads to variability in the car repair process, resulting in an increase in the time buffer and impeding the efficiency of the more important, value-adding activities.

When a train contains more defective railcars than normal, there is a negative impact on productivity. Data from one Class I railroad terminal indicates that repair time for wheelset replacement increases non-linearly as the number of bad orders per train increases (Figure 3), suggesting a loss in repair efficiency as the number of bad ordered wheelsets increases.

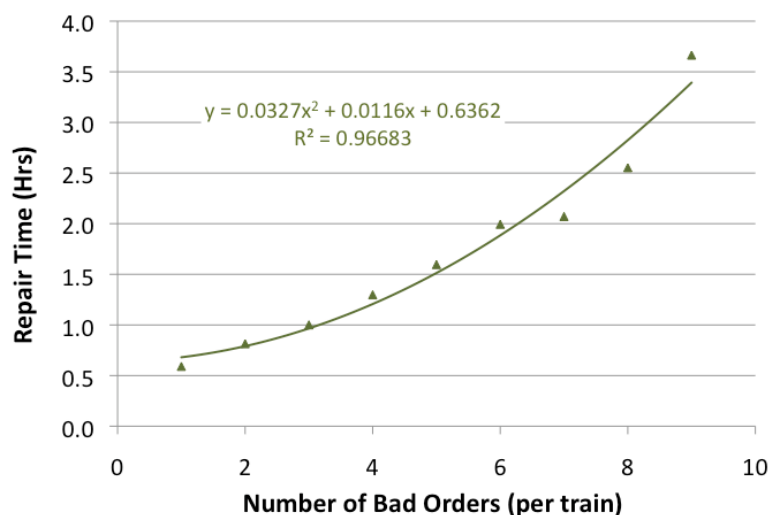


FIGURE 3. Average wheelset replacement times at a major US Class I railroad terminal, 2008-2009

In order to maintain a high level of efficiency, the variability in the number of required repairs should be reduced. A lean production method of reducing variability is to regulate work-in-process (WIP) levels. WIP is the amount of unfinished product that is moving through the manufacturing system at a given time. In the context of railcar inspection, condition-based maintenance can help regulate WIP and reduce variability. Condition-based maintenance is a form of preventive maintenance based on vehicle performance and/or parameter monitoring and involves taking corrective action prior to component failure (24). If wayside detection thresholds are set appropriately, not only can component deterioration be detected at an early stage in order to prevent derailments, but maintenance can be planned efficiently and WIP levels can be regulated to reduce system variability. If the condition of railcar components can be monitored in such a way that a “window-of-opportunity” is identified for all repair types, then railroad managers could potentially select an optimal workload for their repair personnel and facility. Defects that are condemnable by FRA requirements, or otherwise needing immediate attention, would have the highest priority, but less severe defects within the window-of-opportunity would not have to be repaired unless there were sufficient resources to address the specific defect. Using Statistical Process Control (SPC) techniques, decisions could be made regarding wayside detector thresholds to appropriately reduce car maintenance variability while ensuring that critical defects are repaired prior to failure. These methods would provide railroad

managers the ability to maximize the efficiency of their workforce and reduce time and inventory buffers.

3.4 Continuous Improvement

As new inspection technologies are developed and implemented, the railcar maintenance process will need to be continually examined and improved. Regardless of how diligently managers pursue the reduction of variability, it will always exist in the production system (13). As a result, railroad management should take an active approach towards balancing time, inventory, and capacity buffers. As the maintenance process becomes more and more predictive, new railcar parts can be ordered as they are needed, rather than keeping large stockpiles of unused parts. As demonstrated by Toyota's JIT production methods, this approach to maintenance will reduce the inventory buffer. In addition, as railcars are maintained more efficiently, car availability and asset utilization will improve. This would allow railroads and their customers to either recover capital investment costs by liquidating underutilized railcars, or seek new business using their existing railcar fleet. If railroads choose to reduce the size of their rolling stock fleets, additional savings may be gained by removing or consolidating storage tracks and lower the capacity buffer. Thus, improvements using lean principles can have major impacts on efficiency across the entire railroad network.

4.0 RESULTS

4.1 Calculation of Current Waste Due to 1,000-Mile Unit Train Inspections

The largest portion of waste associated with the maintenance of railcars is the manual inspection of railcars without defects. As ACMT develops, wayside detection systems will provide the capability of performing comprehensive and autonomous inspection of all aspects of the railcar, leaving inspection personnel with responsibility to verify defects identified by the automated system and make necessary repairs. In this way, waste will be reduced from the time required to inspect an entire train to the time required to inspect several defective (or potentially defective) cars per train.

The greatest initial benefit, in terms of waste reduction, will be reduced labor during the inspection of unit trains. Since these trains often travel long distances, they are required to stop for FRA Class IA, 1,000-mile air brake inspections. Unless the locomotives need refueling or a new train crew, this inspection is the only reason for the intermediate stop. In addition, unit trains will be the first to benefit from ACMT that incorporates machine vision technology. The first generation of many of the computer algorithms required for these systems have been developed to inspect cars that are similar in design. Thus, in the preliminary analysis, the savings for unit train inspections are calculated using data from one Class I rail terminal that inspects a large number of unit coal trains each year.

Train inspection data for this terminal is given in Table 2. In order to quantify the savings due to waste reduction, the annual labor cost required for a hybridized ACMT approach (see Table 1) is subtracted from the annual labor costs for the conventional, manual inspection.

	Train Type				Total
	Coal	Grain	Automotive	Intermodal	
Average Inspection Time (hrs)	2.31	1.96	1.62	1.33	2.16*
Number of Trains					
Inspected per year	10,600	650	770	1,320	13,340
Percentage of Trains					
Inspected per year (%)	79	5	6	10	100

*Weighted average

TABLE 2. Unit Train Inspection Data for an Example Class I Railroad Terminal

4.1.1 Manual Inspection Cost

Annual labor costs for manual Class IA unit train inspections are calculated as follows:

$$C_{manual} = 2 \times T_{manual} = x N \times S \quad (1)$$

where:

C_{manual} = total annual labor cost for manual inspections, in US dollars

T_{manual} = average manual inspection time (weighted by train type), in hours

N = number of 1,000-mile inspections per year

S = average hourly compensation for car inspectors, including benefits in US dollars

The average inspection time, T_{manual} , is determined by taking a weighted average of the inspection times for each train type from Table 2, resulting in 2.16 hours per train. For this terminal, N is equal to 13,340 unit train inspections per year. Converting the average annual salary of a car inspector (\$81,400 including benefits) to an hourly rate, S is equal to \$39.13 per hour (25). This is a conservative estimate, as mechanical department manager salaries have not been included. Multiplying all of these values by two, to account for the fact that most car inspections involve two car inspectors, C_{manual} is approximately \$2,255,300 for this terminal.

4.1.2 Hybrid ACMT Inspection Cost

For this example, we assume a hybrid inspection system where ACMT identifies component defects and flags potentially defective cars before a train arrives in the yard. When the train arrives, car inspectors inspect only the flagged cars and make decisions regarding whether those cars should be repaired or bad ordered or whether they are deemed satisfactory for continued operation. Annual labor costs for hybridized unit train inspections are calculated as follows:

$$C_{hybrid} = (D \times A_{automated} + F_{automated}) \times T_{hybrid} \times N \times S \quad (2)$$

where,

C_{hybrid} = total annual labor cost for hybrid inspections, in US dollars

D = average number of detectable FRA defects per train inspection

$A_{automated}$ = average correct identification percentage for automated wayside detectors

$F_{automated}$ = average false alarm rate for automated wayside detectors

T_{hybrid} = average inspection time to verify a single component defect, in hours

Current wayside inspection technology is capable of maintaining accuracies ranging from 90% to 99% (18, 26, 27, 28), so an average of 95% is used for $A_{automated}$. Although false alarm rates vary widely among systems, an average of 10% was used for $F_{automated}$. For purposes of illustration, I assume that 5 out of 100 trains containing a component defect will pass the wayside detectors without being flagged (95% accuracy) and an additional 10 out of 100 healthy (non-defective) trains will be incorrectly flagged by the wayside detectors (10% false alarm rate). The average inspection time required for a car inspector to verify a flagged railcar, T_{hybrid} , is assumed to be 10 minutes, regardless of train type. Using data from Table 2, the total labor cost associated with a hybridized inspection process is \$422,840 per year. Subtracting this from the labor costs required for the current manual inspection process results in \$1,832,440 of annual labor cost savings for this specific terminal.

These costs are sensitive to both the number of inspections considered, N , and the overall condition of the railcar fleet, represented in this model by D . The introduction of ACMT will increase D because more defects can be detected using a hybrid inspection system than with pure manual inspection. However, as railcar maintenance improves and becomes more preventive due to ACMT, D should decrease over time. To better understand the expected labor costs at varying magnitudes of N and D , a sensitivity analysis was performed (Figure 4).

In all cases, labor cost savings decrease linearly with D . Therefore, as maintenance practices improve, D will decrease and cost savings will increase. Values for N are representative of a single (major) Class I railroad terminal ($N = 10,000$), an entire Class I railroad ($N = 50,000$) and all US Class I railroads ($N = 250,000$). Although these are rough estimates, they enable comparisons among various magnitudes of N . Assuming approximately 250,000 Class IA train inspections per year and less than five detectable FRA defects per train inspection, the US railroad industry would save over \$35 million per year in reduced labor costs. Although they have not been included in this analysis, ACMT can provide additional savings as preventive maintenance strategies increase car utilization rates. As cars are maintained more efficiently, railcar cycle times will decrease and fewer cars will be required to provide the same level of service. This increase in the capacity buffer will result in various management options: 1) liquidate rolling stock assets and recover capital investment costs, 2)

consolidate or remove storage tracks to recover capital investment and maintenance costs associated with underutilized infrastructure, or 3) absorb the additional capacity by pursuing new business. In this way, application of lean principles through the use of ACMT can have additional and far reaching economic benefits.

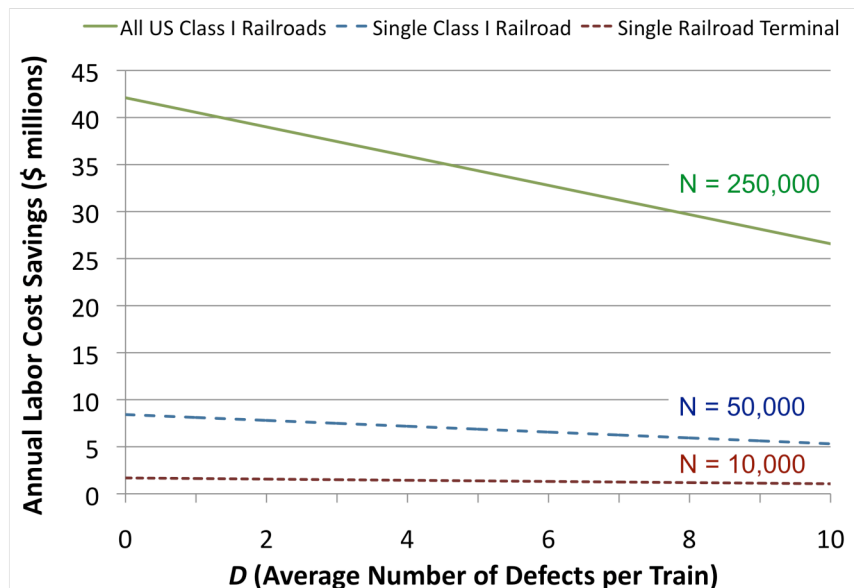


FIGURE 4. Sensitivity analysis showing labor cost savings for varying levels of railcar fleet size (N) and railcar condition (D)

4.2 Summary of Results

This economic analysis indicates that the use of a hybridized machine-search human decision inspection process is approximately nine times more efficient, in terms of labor costs, than pure manual inspection. These results, although limited to a single Class I railroad terminal, demonstrate the potential for significant reduction in operational waste. Although wayside detection technology is not yet implemented to the level where every railroad terminal could benefit from the hybrid process, the efficiency of a large portion of these inspections could be improved by eliminating manual inspection of healthy cars. In addition to these savings, other costs can be reduced through the elimination of other forms of waste, the appropriate allocation of buffers, and the reduction of variability.

5.0 CONCLUSION AND DISCUSSION

Railroad yards, like other manufacturing systems, can significantly benefit from the application of lean production methods. A methodology has been presented for the application of Lean Railroading to railcar inspection and maintenance practices using the four-step approach of: 1) eliminating waste, 2) swapping buffers, 3) reducing variability, and 4) performing continuous improvement. An example Class I railroad terminal was used to calculate the potential reduction in waste, and a savings of approximately \$2.0 million was estimated for a single terminal. If these results are extended to the Class I railroad industry, implementation of the first step of Lean Railroading could save them over \$35 million per year. Through the implementation of steps 2 through 4, additional operational cost savings could be realized.

In order to eliminate the operational waste associated with railcar inspection practices, two industry milestones must be reached. First, automated wayside detection systems capable of monitoring all safety-critical railcar components must be fully developed and integrated. This will require the development of reliable and robust condition monitoring systems capable of addressing every aspect of the FRA Class 1A, 1,000-mile air-brake inspection. When this is achieved, new regulations may then be adopted to allow automated technology to augment manual inspection, resulting in a more effective and efficient hybrid system. The industry has already begun to move in this direction, as regulations have been introduced to allow extended haul trains to travel up to 1,500 miles before stopping for a required inspection (17). In addition, trains equipped with electronically controlled pneumatic (ECP) brakes are permitted to travel up to 3,500 miles before a required air brake inspection (17). As wayside detection systems are further incorporated into railroad mechanical

practices, the distance between inspections may be increased and/or the labor requirements for individual inspections reduced.

6.0 FUTURE RESEARCH

To better understand the potential waste involved in railcar inspection practices, value stream mapping (6) can be performed to determine other potential Type I and Type II waste. This will involve an assessment of the entire railcar maintenance process to identify each individual inspection sub-process, and determine the value and/or waste associated with each sub-process. Variability in the railcar maintenance process can also be further investigated and a methodology can be developed to reduce variability using SPC and Six Sigma techniques. Additional data can also be collected to more accurately extend cost estimates beyond a single terminal, to a significant portion of the US Class I railway network.

This paper is part of a larger analysis considering the costs and benefits of implementing ACMT. Previous work included an economic analysis of the costs associated with train accidents and mainline delays due to defective railcar components (28). Track and equipment damages were calculated and train delay costs were estimated using results from dispatch simulation software. Future research will include an evaluation of the costs associated with the implementation of ACMT including research and development, installation, and maintenance costs as well as the institutional costs of technology integration.

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