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Rail Track Asset Management and Risk Management

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16. Abstract

The United States has the most extensive rail network in the world. Freight rail carries over 43% of ton-miles of goods and passenger rail transports millions of passengers annually. Track infrastructure is the most valuable asset to the rail industry. Also, track infrastructure quality is critical for rail safety and risk management. Despite billions of investment in track construction, inspection and maintenance, there is a lack of comprehensive, coherent framework for rail-oriented track asset management. This project develops a customized Concept of Operations (ConOps) of rail track asset management and risk management, built upon an understanding of existing practice, needs and gaps based on survey with one transit railroad. This report presents a comprehensive literature review of broken rails in rail transit based on the resources covering national guidelines and standards, prior publications, and news from social media. It summarizes the potential factors affecting the occurrence of broken rails with engineering heuristics and references in freight rails to help understanding of non-freight rails. The proposed ConOps is then demonstrated in the rail track asset management and risk management & potential applications. Data needs and the roadmap to implement the ConOps in future practice are also identified. Finally, this report concludes with major findings in broken rail reduction benefits and a future work map.

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1 Introduction

The United States has the most extensive rail transportation network in the world. Rail track infrastructure is the most valuable asset to the rail industry. Asset management covers an asset's entire lifecycle from design, construction and operation through to renewal and disposal and the consequences of each activity. It comprises of all systems, procedures and tools needed to maximize asset availability for a minimum whole-life cost and risk. Therefore, rail-track asset management is a term that has rapidly gained influence in the rail industry.

In its asset management policy document, Network Rail (2018) pointed out that the system is key to delivering "outstanding" value for taxpayers' and customers' money and driving sustainable development. Aligned with its corporate objectives, asset management also contributes to improving safety, supporting economic growth and social opportunities, and minimizing its environmental impact. In this report, the asset management study will focus on the topic of rail defects, which is one common contributor to rail hazards for freight railroads, passenger railroads, as well as transit systems.

As introduced by Cannon et al. (2003), steel rail has been at the very heart of the world's railway systems for about 150 years. Rail failure may cause a catastrophic derailment of vehicles with potential severe consequences (e.g., death, injury, damages to infrastructure and rolling stock, train service delay, and loss of public confidence). One major objective in rail safety is to detect, rectify, reduce, and eliminate rail defects before they cause rail hazards and accidents. Considerable work is being done by railroads to make improvements in rail making and inspections. Meanwhile, broken rail is still a major cause of freight train derailments in the United States (Liu, 2016) and rail defects continue to be a substantial economic burden and a threat to the safe operation of virtually every railway system (both freight and passenger rail) in the world. Thus, it is still essential that international rail supply, operating businesses, rail industries and research centers collaborate to pursue more effective strategies that aim to reduce rail failure risk. This report focuses on the rail-defect-related track infrastructure asset management and risk management.

1.1 Major Components of Railroad Infrastructure

In order to better understand the issue of broken rails, a short section dedicated to depicting how the different parts of railroad infrastructure work together is given here.

The first point of contact in the railway system, the rail, is also the most critical part of the system. Its primary purposes are to transmit forces from the wheel of the rolling stock to the sleeper of the railway and guide the train in the correct direction (Agico Group, 2017; Cannon et al., 2003). After forces are transferred to them, the sleepers (also called crossties or ties) must provide sturdy and uniform support to rail and funnel forces to the ballast as well as align the rails & maintain the correct rail gauge. For these goals to be achieved the sleepers must be laid perpendicularly to the rails (Agico Group, 2017).

A ballast in railroad applications helps railroad tracks by being the bed (of crushed stones) on which tracks lay thus having the purpose of giving track stability, drainage, and support of the loads transferred through the sleepers from the rail. Additionally, this member of the railroad track system is meant to prevent the growth of vegetation and make track maintenance facile (Vulcan, 2013). Likewise, the sub-ballast is a flooring of crushed stone that provides support for the rails and crossties as well as the ballast above it. Although this component offers significant aid in creating a “moister barrier”, it is often one of the first to be forgotten (American Rails, 2019).

Other major elements of the railway system are the rail joint, rail fastening system, and railway turnout. A rail joint is a metal rod on the outside of two steel rails that are linear which is used to connect the end of two rails by fish bolts (Agico Group, 2017). This part is used as an alternative to weld the rails together (American Rails, 2019). The rail fastening system is a reference to a collection of railway fasteners used to fasten the rail to the sleepers. The main purpose of these apparatuses is to impede the rail from movement both laterally and horizontally. Additionally, the rail fastening systems can absorb and transmit forces from the wheels to the sleepers. Lastly, the railway turnout (or railway switch) is a part of the rail-sleeper system that changes the track on which a rolling stock is moving on (Agico Group, 2017).

1.2 Overview

In the age of big data, the railroads will acquire extensive datasets in rail characteristics (e.g., rail age, rail size, track curvature, grade, track geometry exception, turnout, joint or welded), operational conditions (e.g., axle load, traffic density, annual wheel passes), and maintenance activities (e.g., inspection, rail grinding). A well-organized track asset management involving these datasets would contribute to effective rail defect mitigation and prevention and improve the safety level of the railway system.

The structure of this report is organized as follows. Firstly, Chapter 2 presents the literature review of broken rails in rail transit, in which the resources cover national guidelines and standards, prior publications, and news from social media. Additionally, this chapter summarizes the potential factors affecting the occurrence of broken rails with engineering heuristics and references in freight rails to help understanding of non-freight rails. Chapter 3 then demonstrates a Concept of Operations in the rail track asset management and risk management & potential applications. Finally, this report concludes with major findings in broken rail-related transit track asset management and a future work map.

2 Literature Review of Broken Rails

Increasing the safety of transportation by rail continues to be a (nearly) worldwide effort, having benefits in the form of decreased casualties/injuries, maintenance costs, delays, and customer complaints (Cannon et. Al, 2003; Dick et. Al, 2002; Zarembski and Palese 2006). This review focuses on broken rails on commuter and transit railroads in three parts. Firstly, a discussion of recent incidents that portray the dilemma of broken passenger/transit rails was presented. Next, scholarly articles that detail broken rail influence factors specific to passenger and transit rails were summarized. After this section, a short exhibit of recent national guidelines that were made in response to insecurities brought on by broken rail statistics was reported. Finally, although there are differences in broken rail characteristics and consequences between commuter/transit railroads and freight railroads (e.g., axle load, traffic volume in passing cars), an overview of freight-train broken rails is summarized with a particular focus on affecting factors since freight rails have been studied to a much greater extent.

2.1 Broken Rail Caused Accidents on Commuter and Transit Rails

2.1.1 MLK Jr. Day, 2018 Train Derailment

Estimated to have occurred at 6:30 am, a "7000-series" Metro train that had 63 passengers inside derailed just outside the Farragut North Station in Washington DC. The number of passengers was much less than the typical amount of Monday commuters because it was the holiday of Martin Luther King Jr. Although no serious injuries were recorded, passengers' accounts of the event meant that the outcome could have been worse.

One person commented about the emergency brakes doing their job, but that they did not work as quickly as one might think, while some reported a sudden jolt that felt like extreme airline turbulence, and yet another described his experience as hearing a loud bang followed by abnormal shuddering which was then succeeded by a sudden jerk. Afterward, he smelt smoke and strong electricity and was wondering whether things were "about to get worse or better".

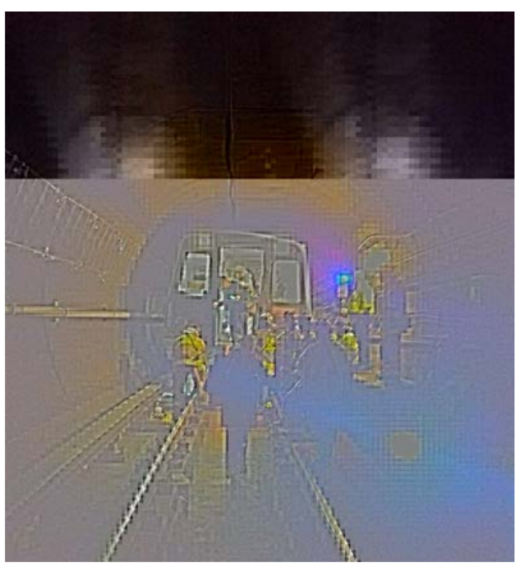


Figure 2.1. Derailed Metro Train (Aratani et al., 2018)

The crew members also made reports, complaining of thick smoke clouds making visibility impossible as they tried to assess damages. It was later confirmed by the General Manager, Mr. Wiedefeld, that the train skid of over 1,200 feet on concrete was the cause of the smoke clouds. He also made statements about the rail age not being the problem since similar rails can be expected to last 40-50 years and that the root cause of the problem had not yet been identified. He did however mention the cracking seen and wondered whether a break in the rail developed over a 10 foot portion of rail (which burst in many different places) as the train moved over it. He also commented that the cleanup procedure would take “some time” because of their methodical approach to avoid further damages (Aratani et. al, 2018).

2.1.2 Incidents of Broken Rails Cause Delays on LIRR

On January 29, 2019, broken rails near Mineola and Wantagh caused yet another day of delays and cancellations on the Long Island Railroad and affected four branches of operation leaving commuters displeased. Reporters claimed that the most probable cause of the broken rails was cold temperature. It should be noted that just the prior week, commuters had to handle a similar situation when three rails broke because of the weather (Long Island News, 2019).

Again, on Thursday, January 31, 2019, the Long Island Railroad had pervasive delays during the morning hours because of broken rails. Commuters were left outside in the “bitter cold” as they withstood delays of up to 20 minutes although some were able to find shelter in waiting rooms provided for the full day. Crew members of the LIRR were assembled to fix rails near the Valley Stream, Huntington, Southampton, and Jamaica stations (Long Island News, 2019).

2.1.3 Injuries, Hours Spent Underground, and Delays Resulting from a Broken Rail

The first of two broken rails found in a matter of days on the Queens F Line of New York Subway occurred on the 2nd of May 2014. This first incident caused the derailment of a subway train which left 19 people injured, approximately 1,000 people trapped underground for multiple hours, and heavily impacted commute schedules. Passengers reported that the train shook, tilted, made very loud metal on metal screeching sounds, and was traveling at a "fast pace" and some said the speed was faster than usual. Services on four lines were suspended and recommendations for alternative travel plans were made by the MTA following the accident. While the shut-down was going on, crew members had to work "feverishly" in order to have the station reopened for the transit of rush hour trains (Sheehan et. al, 2014).

Emergency Responders

Trapped Subway Riders

Figure 2.2. Broken Rail-Caused Subway Train Derailed at 65th and Broadway, New York, 2014

(Sheehan et al., 2014)

Figure 2.3. MTA Investigation of Rail *(Yakas, 2014)*

Later that day, it was found that the region where this event occurred held the second most broken rails record (205) in New York City between 2005 and 2012 (Yakas, 2014). So, when another broken rail was found along the same line three days later, it came as no surprise. Fortunately, the second broken rail was not nearly as catastrophic. It was found in a new rail, during maintenance checks so there were no accidents or injuries caused (Harshbarger, 2014).

2.1.4 A Broken Rail "disrupts trains across the country" In England

In an article released by BBC on the 6^{th} of November 2018, this statement was cited from Network Rail; one of its six lines into the Manchester Piccadilly station had to be closed which adversely affected the service provided to Birmingham, Manchester Airport, and London. On top of this, numerous cancellations were made, 15-minute delays were to be anticipated, a reduction of services for many lines took place and 3 more lines had to be closed overnight.

Network Rail did apologize for the inconvenience and gave hopeful statements that the rail would be fixed during the night (Figure 2.4 is a picture of their official twitter response). Additionally, a bus from Piccadilly to Manchester Airport was temporarily instilled to make up for the lack of rail transport (BBC News, 2018).

Figure 2.4. Network Rail's Twitter Response (BBC News, 2018)

2.1.5 A Report of Broken Rails Displaced 50 Commuters for 15 Hours in Canada

In January of 2018, a story was released concerning 50 Via rail customers being added to the small town of Gogama, Canada for a day after a report of broken rails further along the train's route reached the ears of the train engineer at 4 am. The passengers were finally taken away at 7 p.m. by a bus arranged by Via. The cause of the broken rails was the presence of a “bad wheel” on a freight train. The wheel apparently broke the track in 15 different places, making safe travel an impracticability (CBC News, 2018).

2.1.6 Broken Rail-Related Incident in Philippines

In Manila, Philippines, the Metro Rail Transit-3 (MRT-3) was inspected by a Hong Kong based railway operator in light of the (then) recent accident which injured 38 passengers on the same line. After investigation, he stated that a tragedy is impending if the train’s broken rails are not replaced soon. The inspector continued by saying that the broken rails could lead to a train derailment which could cost a significant number of lives or at the least injure many. In 2011, there were only 4 broken rail incidents. This number grew to 11 in 2011, and then increased to 22 in 2013, meaning that the way the rails were being managed was subpar. Additionally, the operator warned that simply because no derailments had occurred already is no indication that this catastrophe would not happen. Immediate replacement of the rail sections with “severe defects” was recommended along with increasing the amount of stored rail tracks and machine grinding rails to remove defects while in the early stages (Cayabyab, 2014).

2.2 Scholarly Articles of Transit and Commuter Specific Broken Rail Factors

The purpose of this section was to detail the issue of broken rails in passenger/transit railroads. This was be done by summarizing papers which used in-depth analysis to identify the different causes of broken rails, highlighted seemingly promising avenues of successful interventions for existing problems, and discussed problems in the industry of broken rails that are yet to have a solution.

2.2.1 Maintenance and High Traffic Density

Many metropolitan transit lines with large traffic densities, such as the subways of New York, Moscow, and Beijing, (as well as transit lines with less frequent usage and freight lines) have greatly benefited from the "Self-Adaptive Scheduling of Rail Tests" (shortened here to S.A.S.R.T.) (Yang et. al, 2015; Zarembski and Palese, 2005). Stations with high traffic densities are being highlighted here because of the well-documented traffic issues that suggests the need for optimal testing routines to minimize further impedance of traffic without compromising essential testing (Abril et. al, 2008; Gestrelius et. al, 2017; Hojda and Filcek, 2016; Yuan et. al, 2016; Zarembski and Palese, 2005). Additionally, since rail is affected by both capacity limits and fatigue problems, very dense transit/passenger stations must (on a much larger scale than other stations) deal with overburdens due to large loads and the "traffic peaking factor" which lead to broken rails (Abril et. al, 2008; Cannon et al, 2003). The S.A.S.R.T. works by firstly determining a permissible rate of broken rails per mile per year based on the category contents of the train fall into (i.e. whether they include individuals, non-hazardous cargo, hazmat materials, etc.). This rate is appropriately called the "maximum allowable risk" (Zarembski and Palese, 2005).

Building from this, key factors that influence the number of rail break incidents are identified. Some examples of this are traffic patterns, the reliability of non-destructive tests to detect rail defects before reaching critical sizes, and the types of risks that are likely to occur in specific environments since some are more critical than others (Cannon et. al, 2003; Lan et. al, 2019; Schafer, 2008; Tuna et. al, 2016; Yang et. al, 2015; Zarembski and Palese, 2005). After significant factors have been identified a schedule is developed to enforce the maximum allowable risk determined and is continually adapted to reduce the chances that defects go undetected (Xu et. al, 2017; Zarembski and Palese, 2005).

Numerous studies have confirmed the negative relationship between rail testing (non-destructive testing like ultrasonic tests) and rail breaks due to preventative and corrective procedures undertaken after defect recognition such as rail grinding, rail replacements, and welding (Cannon et al., 2003; Dick et al., 2002 Zarembski and Palese, 2005; Zhao et al., 2007).

Figure 2.5. Ultrasonic Test Conducted by Hand *(*Zarembski and Palese, 2005)

Figure 2.6. Ultrasonic Test Done by Vehicle (Railway Technology, 2013)

2.2.2 Corrosion

Either through removal (due to impending failure) or failure, a rail's life can be shortened from multiple decades to less than a year because of corrosion. Known to prominently occur "in tunnels or wet undergrounds", rail base corrosion happens because of galvanic reactions encouraged by the amalgamation of different factors like humidity, inadequate ventilation, water leaks (especially salty water), accrued salt at tie plates and clips, varying metal structure & composition, contamination with dust & like particles, and most importantly the return (DC) current from the traction motors of transit cars (Hernandez, 2009; Guseva et al., 2019). AC current is said to be a minor factor when discussing corrosion since it results in only 1-5% of corrosion caused by the same amount of DC current (Hernandez et al., 2009; Paul, 2015).

When corrosion initiates, propagation is likely to follow since the unique shapes that result from the destruction of rails act as stress concentrators. When the shapes are found at the required geometry and orientation (though relatively rare) rail failure can occur (Hernandez et. al, 2009; Cannon et. al, 2003). Plastic ties and a return stray current system are proposed as the best solutions for rail base corrosion. Additionally, insulated joints are another proposed prevention method (Hernandez et. al, 2009). Figure 2.7 shows "intricate" corrosion at the rail's base which has jeopardized the safety of the rail. Diagram c shows even corrosion along the base of the rail (Hernandez et. al, 2009).

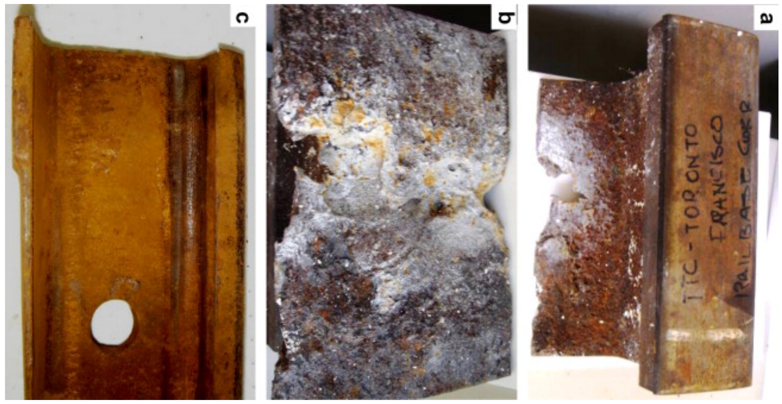


Figure 2.7. Corrosion on Rail Bases (Hernandez et. Al, 2009)

2.2.3 Human attacks

Most likely to occur on or around major transit stations, attacks (e.g. fire promptings or bombings) meant to harm the subway system and/or subway passengers can break rails or significantly decrease equipment resilience which leads to broken rails (Yang et al., 2015; Cannon et al., 2003). In this case, broken rail is the consequence, but it is not the cause.

Figure 2.8. Moscow subway bombing (Levy, 2010)

Figure 2.9. Train after Brussels Explosion *(*Dearden, 2016*)*

2.2.4 Evaluation of Three "Unconventional" Technologies for the Detection of Broken Rails

Since it is known that as more broken rails are detected, the occurrence of broken rail derailments becomes less likely and because it has been concluded that (broken rail) derailments are the most catastrophic accidents, developing ways to minimize and find broken rails is a necessity (Dick et al., 2002; Schafer, 2008; Zarembski and Palese, 2005). In this section, a study funded by the Federal Transit Association (FTA) proposed the implementation of three (3) broken rail detection technologies in the transit sector of railroad activities as alternatives to the track circuit detection method. That is, they do not need track circuits that manage "conventional signal systems, train shunt, or insulated joints" (Kalay et al., 2001).

The first of the three technologies wanted technologies was the rigid bonding of fiber-optic strands to the rail for the early detection of and warning of looming failures, like thermite welds that are partly cracked, separated gages, or broken rails (Kalay et al., 2001; Smith, 2019). The technology works by connecting the strand to a photonix detection system which outputs "major and minor trigger alarms" (Kalay et al., 2001).

The most applicable location of this novel technology is thought to be in “very short, complex” portions of track which are difficult to insulate and have many “ground return paths” (Kalay et al., 2001). This is because of the difficulties encountered during application and reparation procedures. As supported by Yang’s and his colleagues’ statement concerning the labyrinthine inter-station coupling relations of metropolitan transit lines, interlocking segments of track could be the best place to use this apparatus (2015). Nevertheless, the fiber-optic technology has evidenced its ability to reliably find and predict broken rails (Kalay et al., 2001; Smith, 2019).

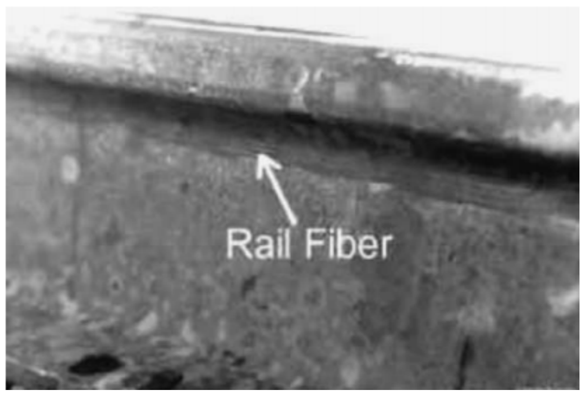


Figure 2.10. Rail Fiber (Kalay et al., 2001)

Figure 2.11. Fiber Application Device (Kalay et al., 2001)

The second procedure suggested is the measurement of longitudinal stresses using strain gages. With this methodology, breaks in continuously welded rail zones can be found hindered by two known cases; The first is the installation of temporary or permanently bolted rail plugs and the second is nominal sensitivity for rails that break but do not disconnect. Still, the lack of needed reparation (unless the actual sensor is flawed) of the sensing system after a break occurs (and the rail is replaced or welded afterwards), provides a lucrative reason to adopt its use (Kalay et al., 2001). The final strategy desired in the effort to find broken rails is the identification of imbalances in the traction current return circuit of the running rails which at the time this study was completed was totally theoretical.

Regardless of whether a “third rail or an overhead catenary system” is used to power an electric rail system, the running rails are utilized as the foundation for the traction current return circuit (now abbreviated to TCRC). The primary goal trying to be attained by the design of the TCRC is to minimize electrical losses which therefore calls for voltage to be minimized. By traveling on the path of “least resistance”, the traction current flows to the electrical substations through the return circuit. As a general rule, the running rails of multiple tracks are joined to create a “multiple-branch electrical network” so as to diminish the return circuit impedance as well as decrease the propensity for “stray current to flow in trackside structures”.

The electrical bonding previously discussed is done to make sure that enough current “flows along and transfers among” the different rail segments. Due to the interconnected network, all running rails should carry traction return current (including current from trains on nearby tracks). Using this fact, the researchers conclude that since current flow in any running rails can only be disrupted by a broken rail or rail joint bond, weird current flows in cross bonds that occur to evade the "discontinuity in the return circuit" should be studied. Their hypothesis is that if this imbalance of current can be consistently be spotted then a new and cheap form of rail break detection would emerge (Kalay et al., 2001).

2.2.5 Composite Subway Brackets Improve Contact Rail Life

Historically (represented by Figure 2.12), support brackets clamped to contact rails in subways have used metallic structures created from channel bars. This makes them very heavy, inclined to corrosion, and capable of becoming energized since they are conductive. Additionally, the structure of the bracket is complicated and laborious to inspect (e.g., insulation is not easily controlled because of the welded box) (Fedulov et al., 2016). As discussed earlier, incidences of corrosion and lessened inspection increase the risk of broken rails (Dick et. al, 2002; Hernandez et al., 2009; Schafer, 2008; Zarembski and Palese, 2005). Using composites for the construction of subway support brackets has been identified as a "very effective" method to achieve increased subway bracket lifespans (Fedulov et al., 2016).

Figure 2.12. Metallic Support Bracket (Feduloy et al., 2016)

Figure 2.13. Composite Support Bracket (Feduloy et al., 2016)

Although compound polymer structures like the structural glass-fiber reinforced plastic (GFRP) are more expensive than traditional materials used in structural applications they are competitive in other applications especially when weight and corrosion are pivotal issues. The composite design shown in Figure 2.13 has a much simpler bracket assembly, is not nearly as heavy whilst having an increased dependability/lifespan and has promises of security from electric malfunctions with superior insulating capabilities (Fedulov et al., 2016).

To improve cost-efficiency, different industries implement massive “integral structures” that have low production costs. When proceeding in this manner, an experimental trial and error method is usually employed to regulate the amount of deviations from specified limits in the final product dimensions. These alterations, called “process-induced distortions”, are caused by “thermal deformation and chemical shrinkage.” If these are not adequately prevented, then difficulties/impossibilities in fitting complex structures’ components properly are likely to arise and poor installation is known to lead to rail defects (Cannon et al., 2003; Fedulov et al., 2016).

2.2.6 Restraining Rails Used by Transit Systems to Improve Safety

Restraining rails, also called guard rails or girder rails, are mainly employed (mostly by transit lines) to bolster the performance of vehicle curving, decrease the chances of flange climb derailment, and manage wheel/rail (W/R) wear (Shu and Wilson, 2007). The improvement of vehicle curving, and the management of W/R wear, are especially pertinent to this review since they are big factors in the manifestation of broken rails (Cannon et al., 2003; Jin et al., 2016; Magel et al., 2016; Sheinman, 2012).

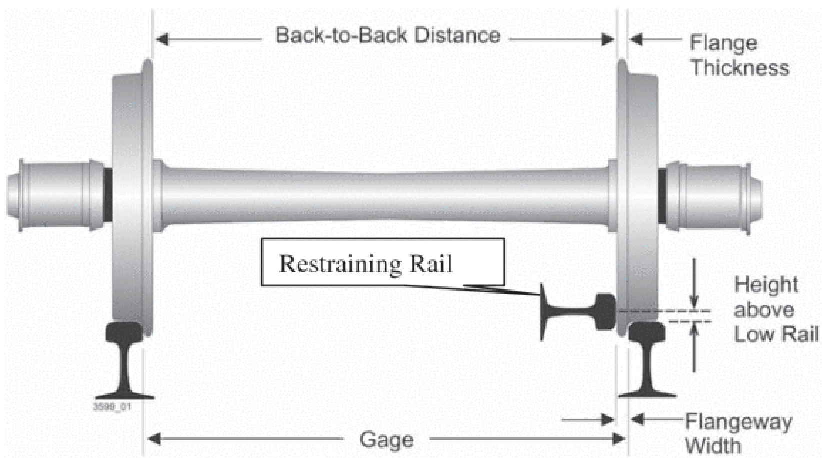


Figure 2.14. Restraining Rail Geometry (Shu and Wilson, 2007)

Figure 2.15. W/R Contact with Guard Rail (Shu and Wilson, 2007)

According to Shu and Wilson in their summary of the TCRP "Restraining/Guard Rail" project, the best guard rail characteristics produces balanced lateral W/R forces and balanced wear between the high rail and the restraining rail. The former can be achieved through the regulation of the flangeway width and the latter by the government of W/R friction coefficients. The wheel profile shape (which consists of the flange back profile, wheel back-to-back distance, track gage, guard/girder/restraining rail profile shapes, installation height, and wheel-set angle of attack (AOA) or the track curvature) is the primary determinant of whether the ideal flangeway width is attained. While inappropriate flangeway widths also increase the wear (either on the high rail or guard rail), proper application of lubricants is the central factor in reaching the goal of uniform wear (Shu and Wilson, 2007). For more details on the study conducted, the original document should be consulted.

2.3 National Standards for Transit and Passenger Broken Rails

In this section, the guidelines/standards pertaining to broken rails set by the Federal Railroad Association (FRA) and the Federal Transit Association (FTA) are presented. The FRA has responsibilities for managing the safety of the USA's railroad system and development of intercity passenger rail through many means such as Legislative Rules, and Management & Procedural Rules (FRA, 2016). Similarly, the FTA administers monetary and technological aid to "local public transit systems" like subways, light rail, commuter rail, trolleys, ferries and buses. It also manages safety regulations as well as assists in the development of next-generation technology research (FTA).

2.3.1 FRA Regulations and Reports

The Track Safety Standards; Improving Rail Integrity (abbreviated IRI for the purposes of this paper) is a legislative document released by the FRA to improve the quality of passenger and freight trains. These IRI codes became effective on the 25th of March 2014. Generally speaking the codes augmented the process for rail flaw detection (established the minimum standards for the operators of the rail flaw detection equipment, updated requirements for "effective rail inspection frequencies, rail flaw remedial actions, and rail inspection records", and got rid of the mandatory reporting of joint bar fractures). A more in-depth review of the codes is presented below.

- Defective Rails: owners of the track have a four-hour window where they must verify that rail sections that are suspected to have defects indeed have them. This was done in order to help track owners improve both the utilization and production of the detector cars, increase the likelihood of identifying major defects, and make sure that all parts of the rail that are meant to be inspected are indeed inspected. Additionally, the burden of stopping all activities to search out a possible defect upon suspicion was lifted. (This was done to avoid civil penalty liability). This reduces the amount of inspections that have to be carried out per day which saved the rail industry $8400 per day.
- Inspection of Rail: The uniform rules about accumulated tonnage (every 40 millionth or so gross ton or once per year, the rail was to be inspected) were disregarded because of the "self-adaptive scheduling method" where the frequency of inspection per year is determined based on factors like "defect rate per test, the rate of service failures between tests, and the accumulated tonnage between tests".

Instead, the final rule mandates that owners of tracks keep service failure rates at a maximum of .1 service failure per year per mile of track for every Class 4 and Class 5 track and no more than .09 service failure per year per mile of track for all Class 3, 4, and 5 track that carries regularly scheduled passenger trains or is a hazardous materials route; and no more than .08 service failure per year per mile of track for all Class 3, 4, and 5 track that carries regularly-scheduled passenger trains and is a hazardous materials route Additionally, it is required that rail inspections on Class 4 and 5 track and Class 3 track with regularly scheduled passenger trains or that is a hazardous material route, cannot exceed 370 days between inspections or a tonnage interval of 30 mgt between inspections (whichever is shorter). Internal rail inspections on Class 3 track without regularly scheduled passenger trains and that is not a hazardous materials route have to be inspected at least once a year, with no more than 18 months between inspections or at least once every 30 mgt (whichever interval is longer). Nevertheless, in no case can inspections be more than 5 years apart.

- Qualified Operators: For a rail flaw detection test to be considered valid, it must be conducted by a qualified operator. A qualified operator must have completed minimum training, evaluation, and have appropriate documentation. Additionally, each provider of rail flaw detection must have a documented training program to make sure that flaw detection equipment operators are indeed qualified to provide this service.
- Records of Inspection: Inspection records must include date inspection was conducted, track identification & corresponding mileposts, type/size of defect found if any, and initial remedial actions required. Additionally, if tracks don’t get a valid inspection, this should also be recorded

- Removal of the Required Joint Bar Fracture Reports: Since the report for every cracked or broken welded rail (CWR) joint bar provided little useful data, the Joint Bar Fracture Reports were to be replaced with a new study that attempts to conclude what circumstances cause/contribute to CWR joint bar failures.

  On top of that, the characterization of the track properties near the failed joint(s), the track geometry (gage, alignment, profile cross level) at the joint location, and the historical maintenance where the joint is located is to be included in the report as well as photos of failure
- The final rule total net benefit was estimated to be around $62.9 million over 20 years.

2.3.2 FTA Regulations and Reports

The State Safety Oversight (SSO) Program became effective in April 2016 (replaced former SSO program). The SSO Program distributed the responsibility of managing transit rail safety to corresponding states while providing minimum requirements for safety regulations in areas like having enough workers and regularly scheduled safety tests (FTA, 2016). Based upon the SSO program, the Two-Hour Accident Notification Guide was published by FTA (2018). This rule states that when an accident (e.g., broken rail-caused derailments) occurs, the rail transit agency must notify both the overseeing SSO agency for the region and the FTA within two hours of any accident occurring on its rail fixed guideway public transportation system (FTA, 2018). In New Jersey, the New Jersey Department of Transportation (NDOT) (2018) identified the broken rail as the first source of rail system damage/problems that may disrupt service. The broken rail-related incident logs should be collected monthly as one of the NJDOT SSO Program general procedures. Besides, NJDOT (2018) also stated that the Train Control System (TCS) provides the functions of on-board speed enforcement that is applied for reasons of civil restrictions, train touring and train separation and for protection against broken rails.

2.4 Summary of Potential Factors Affecting Freight-Train Broken Rail

Since transit and commuter rails have been studied to a much smaller extent than freight rails, this section provides analysis of freight rails in areas that were not discussed in the transit and commuter rails section. Freight trains, particularly loaded freight trains, have higher load on rail tracks comparing to passenger trains, commuter trains, or transit trains. Through various experiments conducted on railway, Frýba (1996) noted that vertical load, for statistical analysis, should be taken in the range of 180–200 kN for fully loaded freight cars and locomotives, 100 kN for passenger cars and partially loaded freight cars, and 50 kN for empty freight cars. This section primarily provides an overview of potential factors affecting broken rail regarding freight trains, based upon the previous broken rail researches.

Although freight-train derailment rates in the U.S. have been reduced by 44% since 2010, train derailment is still the most common type of freight train accident in the U.S. According to data from the Federal Railroad Administration (FRA) of USDOT, 5,100 freight-train derailments occurred between 2000 and 2016, causing 1.7 billion dollars' worth of infrastructure and rolling stock damage (FRA Rail, 2017). A train derailment can have various causes. The FRA of the U.S. Department of Transportation (USDOT) classifies 389 distinct accident causes related to infrastructure, rolling stock, operations, and signaling. Among all freight-train derailment causes, broken rail has consistently been the leading cause in recent years (Figure 3.1). As a result, broken rail prevention and risk management have long been a major activity in the U.S. railroad industry. In addition to the United States, other countries with heavy-haul railroad activity have also identified the crucial importance of broken rail risk management (Kumar, 2006b; Zarembski, 2009).

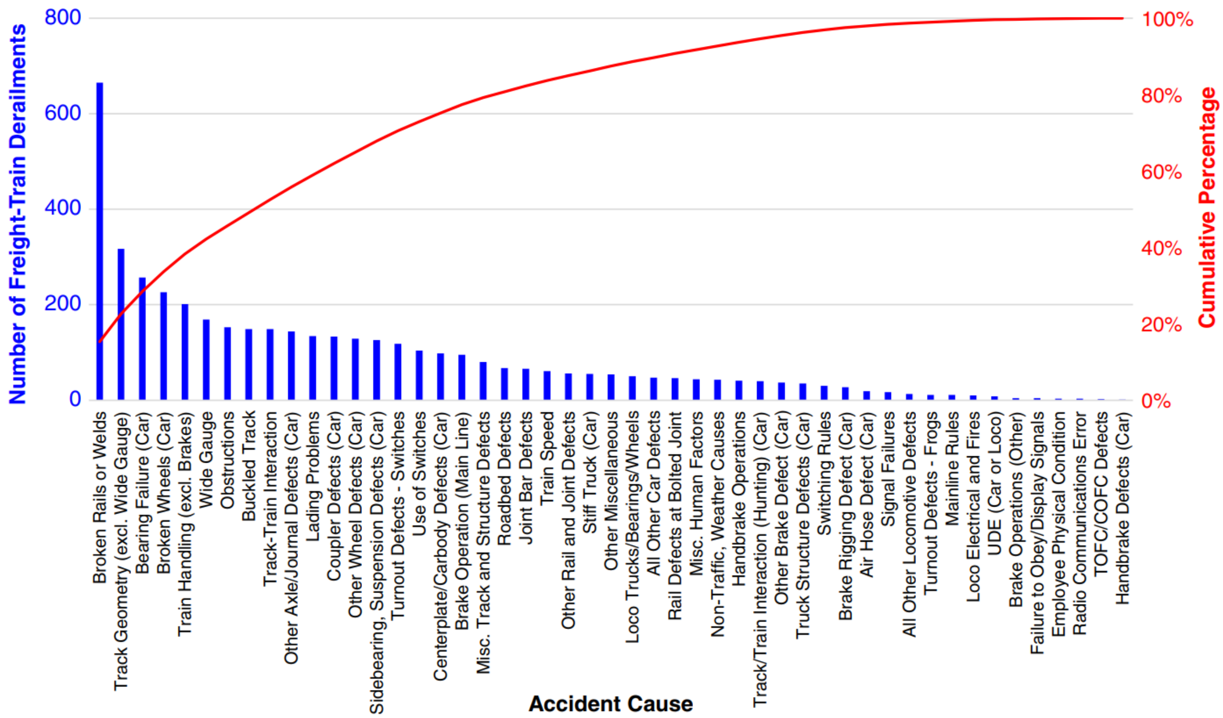


Figure 2.16. Class I Mainline Freight Train Derailment Frequency by Accident Cause Group, All Types of Tracks, 2001 to 2010 (Liu et al., 2014)

There has been growing interest in broken rail research in academia, as demonstrated by an increasing number of publications on this subject. The aim of this section is to provide an overview of these studies, with a focus on statistical and data analytic approaches to predicting broken rail occurrence based on influencing factors. As the rail industry increasingly embraces the opportunities presented by the age of big data and predictive maintenance, data-driven models will continue to increase in popularity. The merits and limitations of various data models are reviewed here, as well as identifying factors and data needed for broken rail risk analysis. Finally, we will suggest possible future research directions on this subject.

Most rail defects are detected and treated before they deteriorate into a critical defect (Kumar, 2006b). Broken rails are linked to many factors affecting one or more processes of rail defect development, including defect initiation and propagation. This study divides contributing factors into five categories: operational conditions, rail profile, rail geometry and layout, defect history, and maintenance strategies. The references citing these contributing factors are shown in Table 2.1.

Table 2.1. Literature by Influencing Factors

Factor	**Observation**	**References**
Rail age	Increased probability of rail defects associated with increased rail age.	Chattopadhyay and Kumar, 2009; Dick, 2001; Dick et al., 2000, 2003; Jeong, 2001; Roney and Ebersohn, 2001; Shyr and Ben-Akiva, 1996
Rail size	As rail size increases, rail defect probability decreases.	Dick, 2001; Dick et al., 2000, 2003; Shyr and Ben-Akiva, 1996
Track curvature	Curved track associated with higher rail defect risk than tangent track, all else being equal	An et al., 2017; Dick, 2001; Dick et al., 2003
	No consistent conclusion is obtained. Although curved sections of rails have greater rail stress, they usually have higher frequency of replacement than tangent rails.	Chattopadhyay and Kumar, 2009; Shyr and Ben-Akiva, 1996
Grade	Steep grades increase the risk of rail defect.	An et al., 2017; Dick, 2001; Stock and Pippan, 2011

Maximum allowed speed	Higher maximum allowed speeds cause higher probability of rail defect.	Dick, 2001; Dick et al., 2000, 2003; IHHA, 2001; Reddy, 2004; Shyr and Ben-Akiva, 1996; Sun et al., 2011
	Higher maximum allowed speed is correlated with better track geometry, counteracting the effect of higher dynamic. wheel load	Dick 2001; Dick et al., 2000, 2003; Shyr and Ben-Akiva, 1996
Axle load	Increases in axle loads cause more bending and shear stresses in the rail which might increase dynamic effects and increase rail defect risk.	Brouzoulis, 2014; Clayton, 1996; Dick et al., 2003; Esveld, 2001; Farris 1996; IHHA, 2001; Kumar, 2006a, 2006b; Reddy, 2004; Zerbst et al., 2009a, 2009b
Traffic density	Higher traffic density causes an increase in rail defects, especially surface-initiated defects.	An et al., 2017; Brouzoulis, 2014; Dick, 2001; Dick et al., 2003; Jeong et al., 1997; Kumar, 2006a, 2006b
Annual wheel passes	Higher number of annual wheel passes is associated with higher rail defect risk.	Algan and Gan, 2001; Brouzoulis, 2014; Dick, 2001; Dick et al., 2003; Shyr and Ben-Akiva, 1996; Skyttebol et al., 2005
Track geometry exception	Presence of geometry exceptions increases probability of rail defects and reduces the life of a rail.	He et al, 2013, 2015; Reddy, 2004; Zarembski and Bonaventura, 2010; Zarembski et al., 2016
Turnout	The presence of turnouts increases the rail defect risk.	An et al., 2017; Dick et al., 2003; Kassa and Nielsen, 2008; Sun et al., 2011
Rail grinding	Rail grinding might delay the	Burstow et al., 2002; Kumar, 2006a,

	occurrence of rail corrugation and reduce the probability of rail defects.	2006b; Reddy, 2004; Shyr and Ben-Akiva, 1996; Zarembski, 2005; Zarembski and Palese, 2010; Zhao et al., 2007a, 2007b
Ballast cleaning	Ballast cleaning reduces the risk of rail defects.	Kumar, 2006a, 2006b
Temperature	There is a higher probability of broken rails in colder weather.	An et al., 2017; Dick, 2001; Jeong and Gordon, 2009; Jeong et al., 1997; Kumar, 2006a, 2006b; Liu et al., 2013; Skyttebol et al., 2005; Zerbst et al., 2009b
Joint or welded	Welded rails suffer less impact loading and have lower rail defect risk.	Dick et al., 2003; Dick, 2001; Zong et al., 2013
Traction/brake section	The presence of a traction/ brake section is prone to cause broken rails.	An et al., 2017
Inspection	More inspections decrease the risk of broken rails.	Dick, 2001; IHHA, 2001; Kumar, 2006a, 2006b; Sourget and Riollet, 2006
Lubrication	More lubrication decreases the risk of rail defects.	Thelen, 1996

3 Concept of Operations in Rail Transit Asset Management and Risk Management

3.1 Overall Methodology

A Concept of Operations for rail track asset management is proposed in this section. Due to the cultural factor, the organization structural factor, and technical factors, rail track-related datasets are organized and accessed by different departments of one railroad and are isolated from the rest of the organization that is one common data management phenomenon called as data silo. In addition, there are other challenging issues existing in datasets, such as format, duplicates, missing data. In order to overcome the impediment to effective decision making raised by data silos, this section aims to present a systemic methodology in the rail track asset-related data management that involves four steps: essential dataset identification and collection, data cleaning and mapping, comprehensive database integration, and data analysis and modeling.

- Essential data identification: Identification and collection of needed databases in the rail track asset management
- Data cleaning and mapping: general approaches in dataset reformatting, duplicate cleaning, missing data makeup
- Data integration and comprehensive database development: combining data from different sources into a single, unified database view so that employee and/or clients can easily access data from the master server involving compreshenvie database
- Data analytic algorithms and modeling: common data analytic methodologies in supporting the analysis and mitigation strategies of broken rail along with model implementation and evaluation

It is also acknowledged that there is no completely universal approach to data integration. However, data management solutions typically involve a few common elements that are demonstrated in this section. The objectives of the proposed Concept of Operations in track asset management are to improve collaboration and unification of data systems, boost efficiency, reduce errors and avoid rework, deliver more valuable data and leverage big data in the rail track asset management and broken rail prevention.

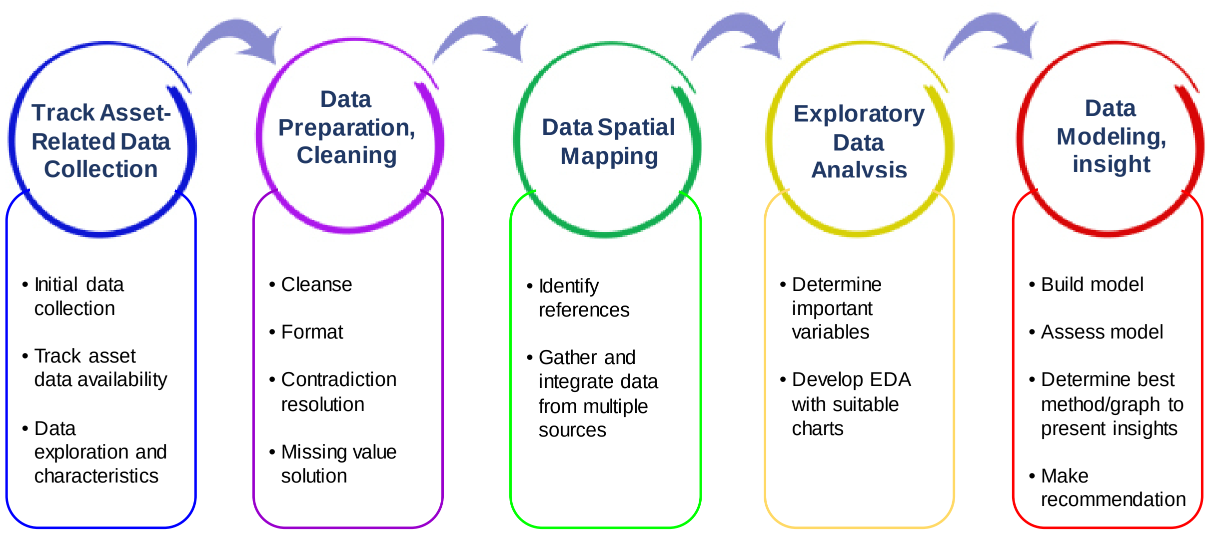


Figure 3.1. Major Process Steps in the Concept of Operations in Track Asset Data Management

3.2 Data Needs

Broken rails are linked to many factors affecting one or more processes of rail defect development, including defect initiation and propagation. As a study of broken rails-related track asset management, the data focuses on five categories, namely operational conditions, rail profile, rail geometry and layout, defect history, and maintenance strategies. More specifically, broken rail-related track asset management includes following datasets that come from various sources. In practices, only part of these datasets is directly accessible. For example, in the cooperation with one transit railroad, track charts, broken rail historical data, and geometry inspection data are available for the research team. They cover track files data, rail service failure data, geometry exception data, rail laid information, track curve, track grade, track turnout, and track signal data.

Table 3.1. Potential Datasets in Broken-Rail Related Track Asset Management

Data	**Description / Expected Content**
Track File Data	Rail type of track segment. A specific segment specifies the start and ending milepost locations of route identifier and track number
Rail Service Failure Data	Data of service failures that occurred in the network
Rail Defect Data	Data of detected defects that were detected, including defect cause, defect location, and remediation action
Geometry Exception Data	Geometry defects detected by geometry car. The geometrical parameters of track include alignment, profile/surface, elevation, and track gage
VTI Exception Data	Vehicle-track interaction exception that covers car body accelerations, truck frame accelerations, and axle accelerations in both vertical and lateral directions
Tonnage Data	Tonnage measured by segment within specific period (e.g., daily, monthly, and yearly), such as gross tonnage, tonnage on each axle, number of gross cars, and car pass data
Grinding Data	Actual grinding pass data, including both low rail passes and high rail passes
Ballast Cleaning Data	Ballast cleaning history data
Rail Laid Information Data	Year rail laid, rail quality, rail weight, joint or continuous welded rails (CWR)
Track chart	Track profile data, division, subdivision, track alignment, and maximum allowed speed
Track Curve Data	Curvature properties of the curves present in the network, such as degree of curvature, length of curvature, direction of

Data	Description / Expected Content
	curvature, super elevation, offset, and spiral lengths
Track Grade Data	Vertical slope of the track measured in degree
Track Turnout Data	Turnout data of the rail network, such as turnout direction and turnout size
Track Signal Data	Signal distribution in the network, including signal location and signal code (e.g., CSS: cab signal system; TWC: track warrant control; ABS: automatic block signal; YL-S: main track yard limits signaled)
GIS Data	Geographic information system data to show the key track network spatially and geographically

3.3 Data Preparation and Cleaning

Given the amount of data received from a variety of data sources, it is critical to develop a comprehensive database structure that would allow access to data and follow up analyses. However, there are two major issues to achieve a valid track asset management tool; data formatting and data mapping. Databases that are generated by different platforms or from various departments have their own formats and to facilitate data fusion, data reformatting should be the first step in data integration. To map databases and ultimately integrate them into one comprehensive database structure, data can be referenced to track location-based prefix (or division, subdivision), milepost (MP) and track number or GPS coordinates (latitude and longitude). Though longitude and latitude provide an accurate location, a large portion of data sets did not have these coordinates, the milepost location was used to overlay each raw data information to the comprehensive database. Besides, data cleansing may be essential to remove data noises (e.g., duplicate records and missing values).

Table 3.2. Challenging Issues in Data Preparation

Issues	Possible Solutions
Duplicate data	• Drop either one • Keep worst case only
Missing data	• Fill manually • Fill computed values • Ignore
Noisy data	• Clustering • Remove manually • Binning
Inconsistent data	• External Reference • Knowledge engineering tools

3.3.1 Data cleansing in Duplicates

The track-related datasets are commonly recorded manually and/or collected from the field. There are potential mistakes in collecting data which would make the data dirty and noisy. One of the common issues in data analysis is the duplicated data record. There are two common types of data duplications:

(a) two data records (each row represents a data record) are exactly the same and

(b) more than one record associated with the same observation, but the values in the rows are not exactly, which is so-called partial duplication.

To determine the duplicates, selecting the unique key is the first step for handling duplicate records. Selection of unique key varies with the databases. For the databases which are time-independent (it means that this information is not time-stamped) such as curve degree and signal, a set of location information is used to determine the duplicates. For the databases which are time-dependent such as rail defect database and service failure database, using the set of location information alone is not sufficient to identify data duplicates because of potential recurrence of rail defects or service failures on the same location.

Different strategies of handling duplicate records for databases are listed below.

- Record Elimination: For the exact duplication, there are two options for removing duplicates. One is dropping all duplicates, and the other is drop one of the duplicates
- Worst Case Scenario Selection: For the partial duplication, select the worst case. For instance, over the junction of two consecutive curves, it is possible that two different curve degrees are recorded. In this case, we assign the maximum curve degree to the junction.

3.3.2 Missing Value Solution

Handling missing data is one of the most common problems during overlaying information from different data sources to reference dataset. Different solutions are selected according to the cause of the data missing. For example, one reason for the missing data is no occurrence of events on the specific location, for instance, grinding, rail defect, service failures, etc. In this situation, the blank cells should be filled with zeros because they represent no observations of interest of events. The other reason for missing data is that the missing value in the source data. For this type of missing data, a preferred value must be selected to fill it. Take the speed information in the comprehensive dataset as an example, the track segments with missing speed information can be filled with the mean speed of the whole railway network.

3.3.3 Contradiction Resolution

Contradiction is a conflict between two or more different non-null values that are all used to describe the same property of the same entity. Contradiction is caused by different sources providing different values for the same attribute of the same entity. For example, tonnage data and rail defect data both provided the traffic information but may have different tonnage values for the same location. Data conflicts, in the form of contradictions, can be resolved by selecting the preference source based on the assumed more "reliable" data source. For example, both the curvature database and service failure database contain location-specific curvature degree information. If there is information conflict on the degree of curvature, the information from the curvature is used based on the assumption that this is a more "reliable" database for this type of data. The comprehensive database only keeps the value of the preferred source.

3.4 Data spatial mapping and integration

3.4.1 Structured data and unstructured data

The data in track asset management can be divided into 2 groups, structured data and unstructured data. Meanwhile, some of these are from internal resources and the rest are from external resources. An internal resource is stored somewhere under the Project Root Directory. To rail track, it may be structured data like traffic density, financial statements, or unstructured data like track curvature, grade maintenance reports, passengers' feedback and so on. An external resource is stored outside the project, possibly on a local or remote filesystem. An example of this is structured data such as scientific data, government datasets, weather record -- or unstructured data such as financial report of other company, regulation, policy documents, special events, news and so on.

Table 3.3. Types of Datasets

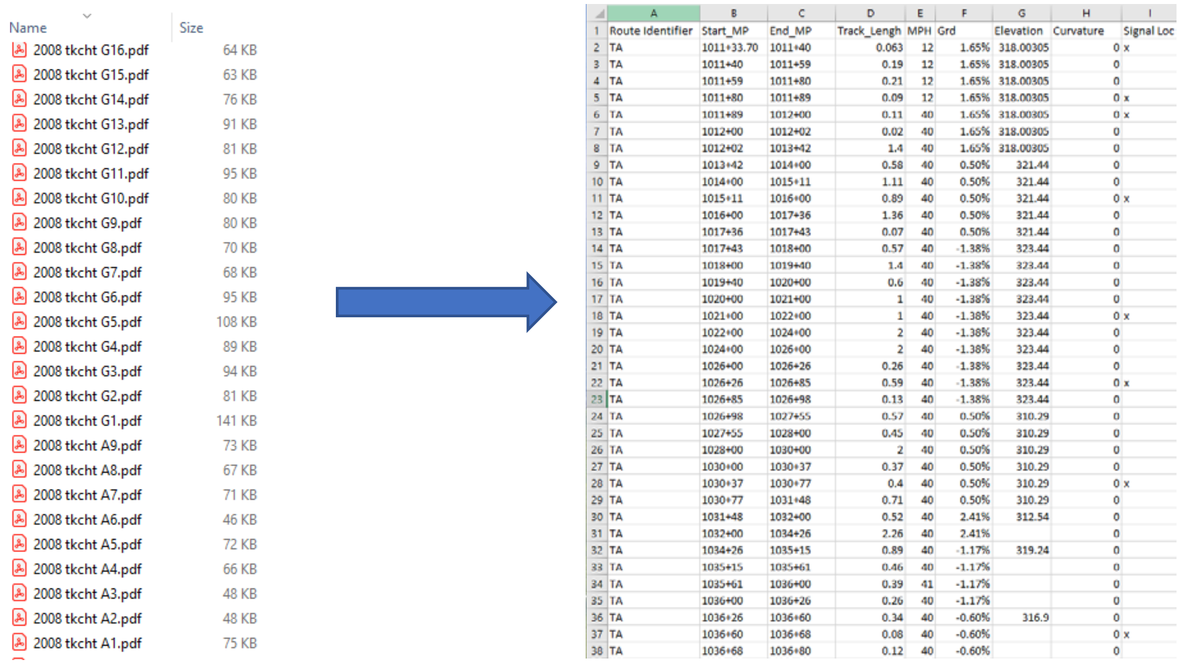
Examples	Internal Resource	External Resource
Structured Data	Traffic density Financial statements	Scientific data Government datasets Weather record
Unstructured Data	Track curvature, grade Maintenance reports Passengers' feedback	Regulation/policy documents Special events/news

First, data from internal sources and external sources needs to be connected. There are three ways to connect the data: 1) connect with external tools; 2) connect data from various sources; and 3) aggregate data from internal sources. The external tools include but are not limited to BCS Meta Man, Data Viewer Web Part, and Lightning Conductor Web Part. More frequently, track asset-related data are aggregated from internal sources without too many external tools. Meanwhile, it is possible that some data is kept in non-Excel file format. It means that the second work in data reformatting is to convert all data information into consistent database form or readable format(s).

In terms of integration of structured data, the key point is to unify the formats of the column names and value types of corresponding columns (e.g., continuous variables or categorical variables) in each database. In particular, below geography-related fields should be highly uniformed that can contribute to ultimate database mapping and integration:

- Route Identifier: coding system with several alphabet.
- Track Type: differentiate between single track, multiple tracks.
- Start MP: Starting milepost of one segment, if have.
- End MP: Ending milepost of one segment, if have.
- Milepost: If have, used to spot the particular point on the track (used for signal)
- Side: Including right side (R) and left side (L) to distinguish different sides of the track.

In addition, it is possible that some data is kept in non-Excel file format. It means that the second work in data reformatting is to convert all data information into a consistent database form or readable format(s). Standard, open, and widespread formats are advisable for long-term track asset data management and data analysis. In general, the data conversions may be as simple such as the conversion of a text filed from one-character encoding system to another. Meanwhile, some can be complex (e.g., the conversion of PDF or audio file). For example, converting from PDF to an editable word processor format is a tough chore, because PDF records the textual information like engraving on stone, with each character given a fixed position and line-breaks hard-coded, whereas word processor formats accommodate text reflow. PDF does not know of a word space character—the space between two letters and the space between two words differ only in quantity. There are two common solution in unstructured data, employment of external tool and manual information extraction. Some simple unstructured files, such as PDF files, may be converted into editable text files, such as Excel or csv format. The other possible solution is to derive information from unstructured data into an organized, structured dataset manually. In the cooperation with one transit railroad, Rutgers research team has completed collecting rail track information from 68 track charts into one well-organized Excel file. Figure 3.2 presents an overview of these charts in PDF format and collected information in well-organized Excel file.



	A	B	C	D	E	F	G	H	I
1	Route Identifier	Start_MP	End_MP	Track_Lengh	MPH	Grd	Elevation	Curvature	Signal Loc
2	TA	1011+33.70	1011+40	0.063	12	1.65%	318.00305	0	x
3	TA	1011+40	1011+59	0.19	12	1.65%	318.00305	0	
4	TA	1011+59	1011+80	0.21	12	1.65%	318.00305	0	
5	TA	1011+80	1011+89	0.09	12	1.65%	318.00305	0	x
6	TA	1011+89	1012+00	0.11	40	1.65%	318.00305	0	x
7	TA	1012+00	1012+02	0.02	40	1.65%	318.00305	0	
8	TA	1012+02	1013+42	1.4	40	1.65%	318.00305	0	
9	TA	1013+42	1014+00	0.58	40	0.50%	321.44	0	
10	TA	1014+00	1015+11	1.11	40	0.50%	321.44	0	
11	TA	1015+11	1016+00	0.89	40	0.50%	321.44	0	x
12	TA	1016+00	1017+36	1.36	40	0.50%	321.44	0	
13	TA	1017+36	1017+43	0.07	40	0.50%	321.44	0	
14	TA	1017+43	1018+00	0.57	40	-1.38%	323.44	0	
15	TA	1018+00	1019+40	1.4	40	-1.38%	323.44	0	
16	TA	1019+40	1020+00	0.6	40	-1.38%	323.44	0	
17	TA	1020+00	1021+00	1	40	-1.38%	323.44	0	
18	TA	1021+00	1022+00	1	40	-1.38%	323.44	0	x
19	TA	1022+00	1024+00	2	40	-1.38%	323.44	0	
20	TA	1024+00	1026+00	2	40	-1.38%	323.44	0	
21	TA	1026+00	1026+26	0.26	40	-1.38%	323.44	0	
22	TA	1026+26	1026+85	0.59	40	-1.38%	323.44	0	x
23	TA	1026+85	1026+98	0.13	40	-1.38%	323.44	0	
24	TA	1026+98	1027+55	0.57	40	0.50%	310.29	0	
25	TA	1027+55	1028+00	0.45	40	0.50%	310.29	0	
26	TA	1028+00	1030+00	2	40	0.50%	310.29	0	
27	TA	1030+00	1030+37	0.37	40	0.50%	310.29	0	
28	TA	1030+37	1030+77	0.4	40	0.50%	310.29	0	x
29	TA	1030+77	1031+48	0.71	40	0.50%	310.29	0	
30	TA	1031+48	1032+00	0.52	40	2.41%	312.54	0	
31	TA	1032+00	1034+26	2.26	40	2.41%		0	
32	TA	1034+26	1035+15	0.89	40	-1.17%	319.24	0	
33	TA	1035+15	1035+61	0.46	40	-1.17%		0	
34	TA	1035+61	1036+00	0.39	41	-1.17%		0	
35	TA	1036+00	1036+26	0.26	40	-1.17%		0	
36	TA	1036+26	1036+60	0.34	40	-0.60%	316.9	0	
37	TA	1036+60	1036+68	0.08	40	-0.60%		0	x
38	TA	1036+68	1036+80	0.12	40	-0.60%		0	

Figure 3.2. Shortcut of Track Chart in PDF Format and Collected Information in Excel

After retrieving the useful information, we will have to create some labels to store the useful information retrieved. To unite the labels, it is necessary to find out which labels have the same meanings so that they can be combined. Furthermore, the conversion itself should be assisted by rail experts who are familiar with the data or the domain, so that railroad experts can check for potential undesirable changes in the data that occurred as a result of the conversion.

3.4.2 Data integration

A reference database with unique length is developed. To capture as many accurate details as possible and to facilitate the data mapping. The unique length in the reference database is set up as 0.1 mile (528 ft). For example, over 19 track-mile network can be represented by over 380 segments with 0.1 mile in length (differentiate the right side and left side of the track). All supplementary attributes from other databases would be mapped into the reference database based on the location index (e.g., route identifier, start milepost, end milepost, track type, and side).

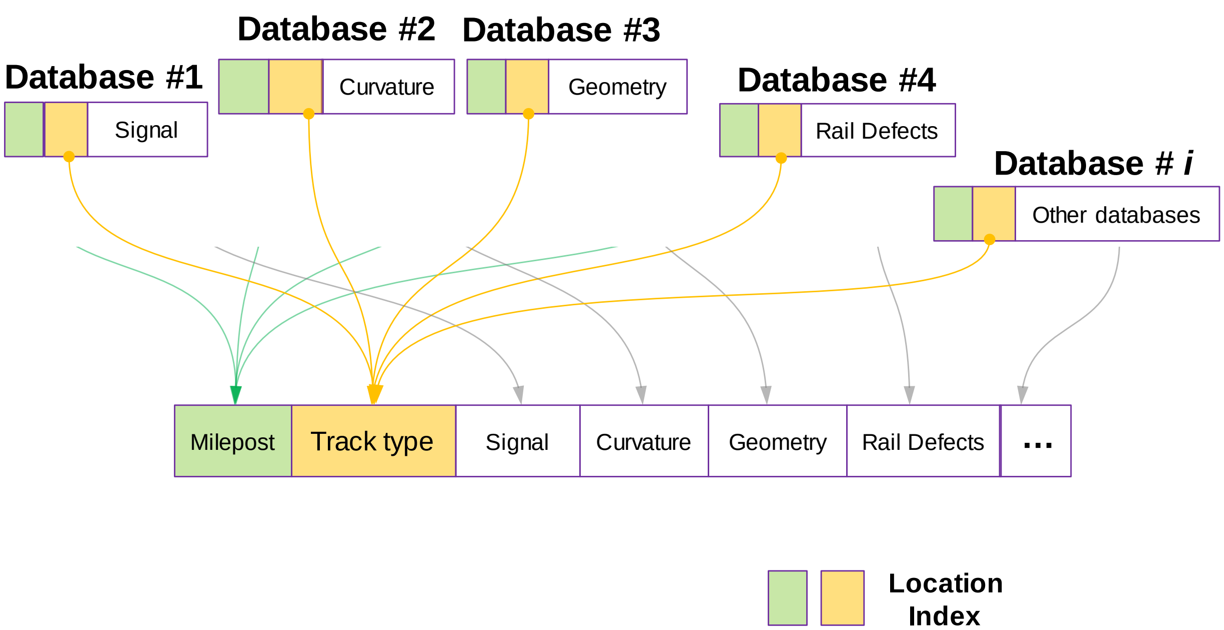


Figure 3.3. Data Integration with reference location

To explicitly illustrate the aforementioned strategy, an example is presented in Figure 4.2. It can be seen that the rail/section location is the main link point between each report. In this way, the rail characteristics, the maintenance and traffic details on one specific rail section from millions of rail sections can be simply and individually selected and shown in the data management tools.

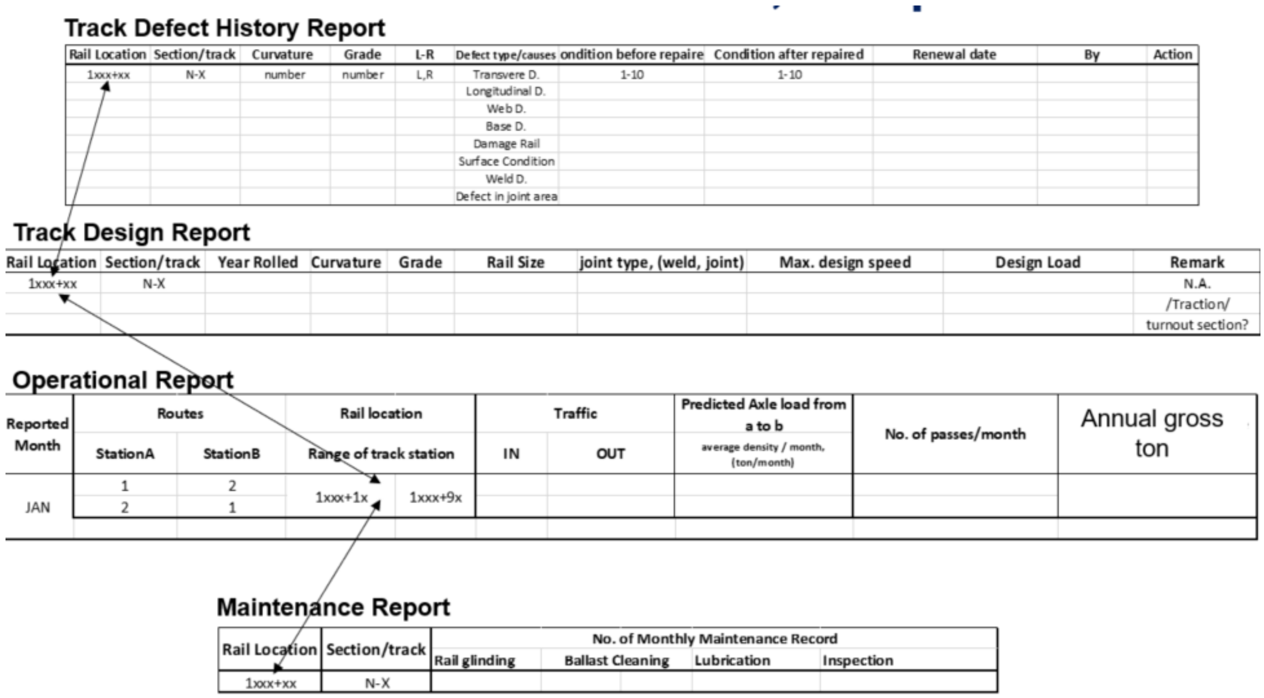


Figure 3.4. Overview of the Suggested Metadata on Each Report

3.5 Data Analytic Algorithms

Two major types of data analysis are commonly conducted in the data exploration and explanation, as well as rail-related data management, exploratory data analysis (EDA) and statistical modeling.

3.5.1 Exploratory data analysis

In the EDA, a series of simple data analysis can be conducted in order to develop a preliminary understanding of the relationship between most of the recorded variables (e.g., variables and information in track, traffic, maintenance, and operational characteristics) and broken rail occurrence. For example, the single variable exploratory data analysis was conducted in the form of the broken rail rate per billion ton-miles. In practice, the following variables may attract more interests and the distributions service failure rate (per billion ton-miles) or broken rail rate (per billion ton-miles) by specific factors can be developed:

- Rail track profile (e.g., rail age, rail weight, track quality)
- Track layout (e.g., curve degree, grade, turnout)
- Maintenance (e.g., rail grinding, ballast cleaning)
- Maximum allowed track speed
- Annual traffic density

Figure 3.5. A Variety of Charts in Exploratory Data Analysis

3.5.2 Statistical Modeling

Statistical modeling in data analysis focus on the utilization of statistical learning or called machine learning in computer science. These are the most widely employed methods in the data analysis and prediction, as a branch of artificial intelligence (AI). The statistical learning-based methods provide the ability to learn automatically from input data (e.g., track asset data) and improve the track asset management from the experience without being explicitly programmed or without the intervention of human. In other words, machine learn algorithms use computational methods to learn and identify information directly from data without relying on a predetermined equation as a model. There are two major categories of statistical learning methods, supervised learning and unsupervised learning (Pilotte, 2016). The choice of algorithms/models depends on the type of task in the data analysis along with the type, quality, and nature of data present.

In the supervised learning, input and output are provided to the computer along with feedback during the training. The accuracy of predictions by the computer during training is also analyzed. The main goal of this training is to learn how to map input to the output. Supervised learning includes two categories of algorithms, classification and regression. The choice of algorithms depends on a number of design factors, such as memory usage, prediction speed, and interpretability of the model. Other considerations include whether a single or multi-class response is needed and if predictors are continuous or categorical.

- Classification: For categorical response values where the data can be separated into specific “classes.” Common classification algorithms include support vector machines (SVM), neural networks, Naive Bayes classifiers, decision trees, discriminant analysis, and nearest neighbor (KNN).

- Regression: For prediction when continuous response values are desired. Regression tasks are characterized by labeled datasets that have a numeric target variable. Common regression algorithms include linear regression, nonlinear regression, generalized linear models, decision trees, and neural networks.

In the unsupervised learning, no such training is provided which left computers on their own to find the output. Unsupervised learning is mostly applied on transactional data. It is used in more complex tasks. It uses another approach of iteration known as deep learning to arrive at some conclusions. The common unsupervised learning methods are K-means, hierarchical cluster trees, Gaussian mixture, neural network, and hidden Markov model. A brief introduction of these algorithms' strengths and weaknesses is summarized in Table 3.4.

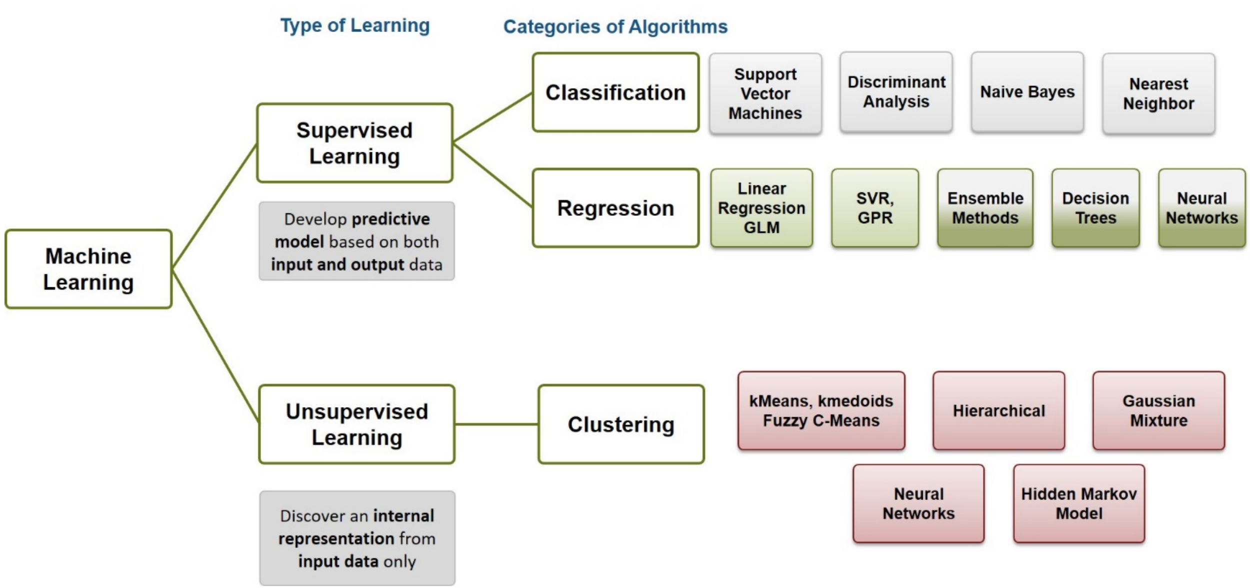


Figure 3.6. Machine Learning-Based Statistical Modeling Methods

Table 3.4. Strengths and Weaknesses of Machine Learning Algorithms

Algorithms	Strengths	Weaknesses
Linear regression	• Straightforward to understand and explain, • Can be regularized to avoid overfitting • Can be updated easily with new data using stochastic gradient descent	• Perform poorly when there are non-linear relationships • Not naturally flexible enough to capture more complex patterns • Assumes the input residuals (error) to be normal distributed, but may not be satisfied always • Assumes input features to be mutually independent (no co-linearity)
Regression tree, decision tree	• Learn non-linear relationships • Fairly robust to outliers. • Ensembles perform very well in practice	• Unconstrained, individual trees are prone to overfitting because they can keep branching until they memorize the training data
Neural Network	• Their architectures (i.e. number and structure of layers) can be adapted to many types of problems, and their hidden layers reduce the need for feature engineering	• Not suitable as general-purpose algorithms because they require a very large amount of data • Computationally intensive to train, and they require much more expertise to tune (i.e. set the architecture and hyperparameters).
Nearest neighbors	• Easily make predictions for new observations by searching for the most similar training observations and pooling their values	• Memory-intensive, perform poorly for high-dimensional data, and require a meaningful distance function to calculate similarity
Logistic Regression	• Outputs have a nice probabilistic interpretation, and the algorithm can be regularized to avoid overfitting. • Logistic models can be updated easily with new data using stochastic gradient descent.	• Tend to underperform when there are multiple or non-linear decision boundaries • Not flexible enough to naturally capture more complex relationships

Algorithms	Strengths	Weaknesses
Support vector machines (SVM)	• Can model non-linear decision boundaries, and there are many kernels to choose from. • Fairly robust against overfitting, especially in high-dimensional space.	• Memory intensive, trickier to tune due to the importance of picking the right kernel, and don't scale well to larger datasets.
Naïve Bayes	• Perform surprisingly well in practice, especially for how simple they are.	• Due to their sheer simplicity, NB models are often beaten by models properly trained and tuned using the previous algorithms listed.
K-means	• Fast, simple, and surprisingly flexible in pre-processing your data and engineer useful features.	• The user must specify the number of clusters, which won't always be easy to do. • If the true underlying clusters in your data are not globular, then K-Means will produce poor clusters.
Hierarchical	• The clusters are not assumed to be globular. • It scales well to larger datasets.	• Much like K-Means, the user must choose the number of clusters (i.e. the level of the hierarchy to "keep" after the algorithm completes).

3.6 Output and Potential Application

There are two major outputs in the broken rail-related track asset management, one is a comprehensive, consistent track asset database, the other one is the broken rail occurrence probability estimation as per machine learning methods and accounting for a set of track-related and operational factors based on the well-organized railroad big data.

<u>A comprehensive track asset database</u>

Developed track asset database is a collection of large datasets related to rail track assets. Different from the raw, separate datasets that cannot be adequately processed using traditional processing techniques, a comprehensive track asset database would cover complete subject and large volume amount of data in both structured and unstructured manners. It mainly contributes to analyzing the in-depth concepts for better data organization, data analysis, better decisions and strategic taken for the safe, economical rail track asset management. With the features in cost reduction and time reduction, developed track asset database has great impact on finding the root cause of broken rails and rail defects in practical operation and further brings smart decision making.

Overall, there are five features in the well-organized track asset database as the output in the Concept of Operations, namely volume, velocity, verity, value, and veracity (Figure 4.7). In terms of volume, the track asset database aims to collect all essential data from relative sources and departments in railroad(s), which include operational conditions, rail profile, rail geometry and layout, defect history, and maintenance strategies. For velocity, the track asset database has great impact in timely manner and streams unparalleled speed of velocity. The developer of any data science can access all data using tools (e.g., Hadoop, Spark, or other programming languages) and engineers can quantitatively check track asset-related data information. The third key feature is variety, in which data comes in all varieties in form of structured, numeric data in traditional databases (e.g., Excel file) to unstructured text documents. Video, audio, and email information can also be converted into text documents and integrated with structured data.

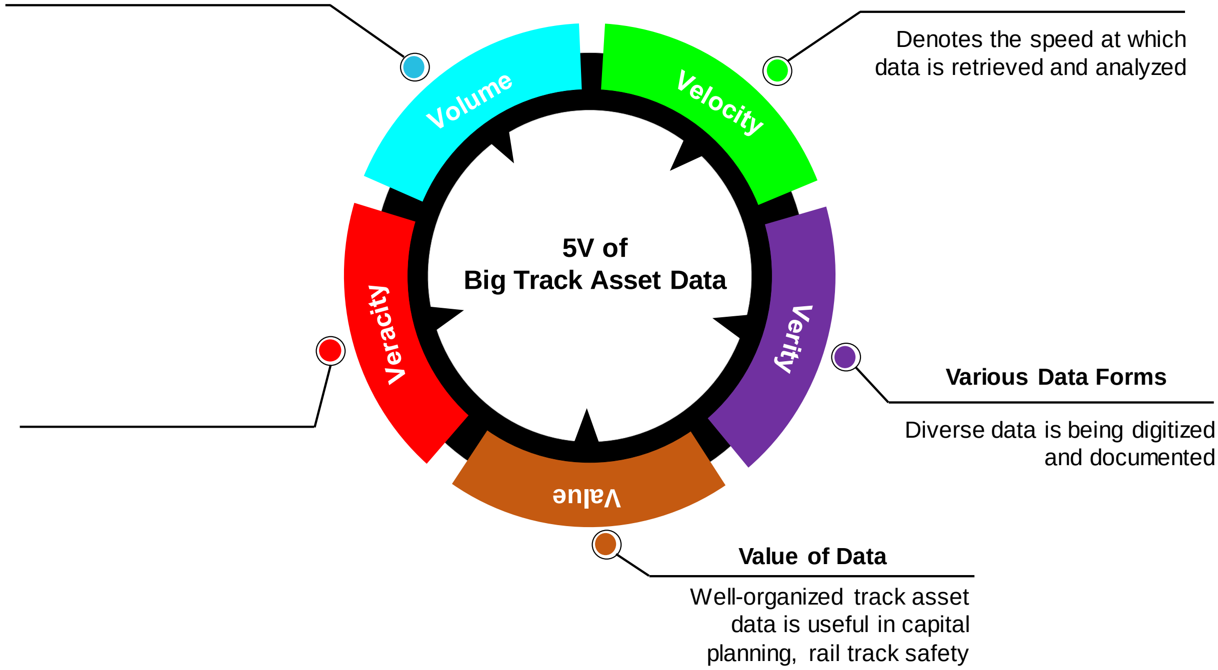


Figure 3.7. Features of Developed Track Asset Management Database

<u>Track asset data analytic tool and results</u>

Well-organized rail track asset data contribute to the development of data analysis and track asset management. In particular, the occurrence of broken rails can be studied and predicted through historical records and rail track asset information. In terms of data analysis, the variables in track, traffic, maintenance, and operational characteristics are analyzed that present a preliminary understanding of the relationships between these variables and broken rail occurrence. The distributions service failure rate (per billion ton-miles) or broken rail rate (per billion ton-miles) by specific factors can be developed with rail track asset-related data and a variety of charts. For example, the distribution of broken rail rate per billion ton-miles by one specific variable, such as rail age, would disclose whether broken rail rate is increasing as the rail age increases, which rail ages have the highest probability of broken rail occurrence based on documented data.

The estimations of broken rail probability, also called prediction, involve two common types of outputs based upon binary classification and multi-output classification:

- binary classification: predict the occurrence of broken rails at a specific time or a specific location; the label of the output in the model is an index value 0 or 1, with 1 indicating the occurrence of the broken rail at one location and 0 representing no occurrence of the broken rail.
- multi-output classification: predict probabilities of broken rails at multiple specific times, such as 0-3 months, 3-6 months, 6-9 months, 9-12 months, and over one year.

4 Significance of Broken Rail Prevention

The proposed Concept of Operations in rail track asset management aims to improve the collaboration and unification of data systems, deliver more valuable data, and leverage big data in the rail track asset management and broken rail prevention. To quantitatively evaluate the significance of broken rail prevention, the safety benefits associated with broken rail prevention are identified in this section. A rapid transit railroad is employed as the case study to disclose the preliminary monetary estimations of broken rail reduction benefits.

4.1 Methodology and Safety Cost Factors

The safety benefits of broken rail prevention are estimated in monetary value based on historical broken rail data and the safety cost factor in each category. The historical broken rail data is presented in the above subsection and the safety cost factor is based upon two major categories per the literature (Liu et al., 2014), the cost of repairing broken rails and the train delay cost due to broken rails.

Cost of repairing broken rails

The AAR developed the following model to estimate the cost for repairing detected defects and broken rails (Wells and Gudiness, 1981). In terms of repairing broken rails, it can be calculated using below equation:

$$SDC = [\frac{W_{replace} \times L_{replace}(P_{new} - 0.95P_{old})}{2000} + C_{Srepair}](1 - t)$$

Where

SDC = total cost for repairing a broken rail accounting for rail salvage value, tax, materials, equipment, and labor cost;

$W_{replace}$=weight of replacement rail in pounds per yard;

$L_{replace}$= length of replacement of rail in yards;

P_{new}=price of new rail, in dollars per ton (800);

P_{old} = price of scrap rail in dollars per ton (200);

$C_{Srepair}$=expenses for labor, materials, equipment, and thermite welds for continuously welded rail ($2,140);

t = federal and state marginal income tax rate (0.53).

In general, an estimated $1,127 was spent to repair a broken rail is provided in Liu et al. (2014) and would also be employed in this simplified safety benefit calculations. Railroad can also update the cost of repairing broken rails per their historical records.

Train delay cost due to broken rail

The time required to repair a broken rail is dependent on its size, type, location, and several other factors. Liu et al. (2014) assumed 5 hours to repair a broken rail but it is acknowledged that the actual repair time will vary depending on circumstances. The FRA report (2009) estimated the cost of passenger train delays, based on 285 passengers per train, an average value of passenger time of $25 per hour. This relatively high per hour value of time is related to the income of train passengers. Many commuter lines have average passenger household incomes in excess of $75,000 per year (FRA, 2009). In addition, the average duration of blockage due to broken rail is estimated as 2 hours.

Per the train schedules and traffic volume of one U.S. transit railroad, it assumes that on average, there are 100 trains and 60 trains passing each line in weekday and weekend, respectively. In particular, there is no train service in the nighttime of weekday. Some routes do not operate during weekend and it assumes that there are no detected broken rails in these routes, although inspection car or signal can still detect the occurrence of broken rails. Based on these, the train delay costs in weekday and weekend are \$445,312 and \$178,125, respectively:

$$C_{weekday} = 285 \times \$25 \times \left(\frac{5}{16}\right) \times 100 \times 2 = \$445{,}312.5$$

$$C_{weekend} = 285 \times \$25 \times \left(\frac{5}{24}\right) \times 60 \times 2 = \$178{,}125$$

4.2 Total Broken Rail Reduction Benefits

Based on the estimations of train delay costs and broken rail repair costs, Table 4.1 presents the monetary benefits of prevented broken rail in two scenarios, low end with all broken rail prevented during weekends and high end with all broken rail prevented during weekdays. For example, if 10 broken rails are expected to be prevented, the reduction benefits are around \$1.8 - \$4.4 million in dollars. For nationwide transit system, there should be a large volume of broken rail occurrences every year. Thus, the broken rail prevention benefits are expected to be significantly high.

Furthermore, this section only considers two parts in benefit analysis, costs for repairing broken rails and train delay costs. Any broken rail-caused accidents (e.gs, derailments) are able to cause considerable damage costs to infrastructure, rolling stock and even casualties. For example, in the benefit-cost analysis guidance, FRA (2016) identified \$9,600,000 per fatality as the value of a statistical life. In the value of injuries, the unit values vary between $28,800 and $5,692,800 that depends on the severity (e.g., minor, moderate, serious, severe, or critical). Overall, the potential consequences resulting from broken rails could be substantial. However, due to the limitation of historical data in transit railroad, this section would not quantitatively cover them in the benefits of broken rail prevention.

Table 4.1. Broken Rail Reduction Benefits by Reduction Percentage per Year

Number of Broken Rail Prevented in One Year	**Monetary Benefits in One Year**	
	Low End (All in weekend)	**High End (All in weekday)**
5	$896,260	$2,232,197
10	$1,792,520	$4,464,395
15	$2,688,780	$6,696,592
20	$3,585,040	$8,928,790
25	$4,481,300	$11,160,987

5 Concluding Remarks

This study mainly provides an insight for the broken rail-related track asset management in the age of big data. The issue of broken rails has proven to be quite pervasive, enduring for more than a century (Dick et. Al, 2002). Having permeated by means of corrosion, wear, crack propagation, etc., this issue has heavily impacted the lives of many individuals through death, injury, sudden/anticipated delays, monetary expenses, fear, and the like. The literature review covering journal articles, news, and federal reports shows the effects of broken rail, corrosion, maintenance strategies and strategies, and the national standards implemented to regulate broken rail occurrence and rectifications.

In practice, due to cultural factor, organization structural factor, and technical factors, rail track-related datasets are organized and accessed by different departments of one railroad and are isolated from the rest of the organization. In addition, there are other challenging issues existing in datasets, such as format, duplicates, and missing data. In order to overcome the impediment to effective decision making raised by data silos, a Concept of Operations for rail track asset management is proposed in this report which aims to present a systemic methodology in the rail track asset-related data management. The proposed Concept of Operation in broken rail-related track asset management involves four steps: essential dataset identification and collection, data cleaning and mapping, comprehensive database integration, and data analysis and modeling. It is also acknowledged that there is no completely universal approach to data integration. However, data management solutions typically involve a few common elements that are primarily demonstrated in this section. The objectives of the proposed Concept of Operation in track asset management are to improve the collaboration and unification of data systems, boost efficiency, reduce errors and avoid rework, deliver more valuable data and leverage big data in the rail track asset management and broken rail prevention. The preliminary quantitative analysis discloses that the preventions of 10 or 25 broken rails are equivalent to around \$1.8~\$4.4 million and \$4.5~\$11.2 million in monetary values, respectively. The potential consequences, such as fatalities and injuries, would also add up the broken rail prevention benefits if any occurs. Overall, the anticipated benefits that accrue from the prevention of broken rail in nationwide transit rail system are expected to be enormous.

Furthermore, there are still additional challenges and future work in the rail track asset management and risk management. Firstly, the integrity of datasets plays a key role in the rail track asset management and risk management. Although developed Concept of Operations aims to reduce the adverse impact from data silo, the lack of certain essential dataset can be the impediment to the rail track asset management, risk management, and effective decision making. Secondly, the occurrence of rail defects and broken rail is a rare event. It is highly difficult to develop a high-accuracy prediction model of the very low probability of broken rail with significantly imbalanced data. Thirdly, in addition to technical impacts, organizational factors and cultural factors may bring challenges in the rail track asset management. For example, in large railroads, data silos can stem from a hierarchy separated by many layers of management and highly specialized staff. As result, one department or team in a railroad can only access a set or source of data. Therefore, to support the efficient rail track asset management and risk management with seeing the big picture, organizational factors and cultural factors should be overcome along with technical factors.

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