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Rolling-stock Automatic In-situ Line Deterioration and Operating Condition Sensing

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Abstract: Track and equipment failures dominate railroad accident causes. Railroads must visually inspect most tracks in service as often as twice weekly to comply with the Federal Track Safety Standards. They augment visual inspections with automated non-destructive-evaluation (NDE) equipment to locate developing and mature defects. However, the defect formation rate is escalating with increasing traffic load density and continuously declining railroad employment per track-mile. This indicates a widening gap between the rate of defect formation and the resources available to find them before they result in accidents, delays, and lost revenue.

With resources thinly stretched and the rate of defect formation escalating with traffic load-density, railroads are seeking to enhance the efficiency of inspections and maintenance of way. This paper describes the development of a Rolling-stock Automatic In-situ Line Deterioration & Operating Condition Sensing (RAILDOCS) system to automatically locate and classify track and rail vehicle defects. The approach incorporates a new low-cost wireless sensor technology and Cloud computing method to guide and focus inspection activities to locations of equipment and track defect symptoms, leading to efficient diagnosis and remediation.

RAILDOCS has on-board sensors which will continuously monitor track and vehicle condition and transmit a 3D inertial signature for a remote processor to analyze and produce a complete and updated picture of aggregate track and equipment quality. RAILDOCS complement more expensive visual and NDE methods by reallocating time spent on defect discovery to detailed inspections of prioritized defect symptom locations. Symptom sensors integrate micro-electro-mechanical (MEMS), global positioning system (GPS) satellite receivers, wireless communications, and microprocessors technology. Cloud computing and signal processing algorithms produce a track quality index, and forecast optimum maintenance triggers.

Keywords: Railway asset management, rail-line deterioration, track and equipment safety, sensing, detection.

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Introduction

Studies show that a combination of track and equipment failures causes over half of all rail accidents around the world.[i] Train accidents in the U.S. have declined 71 percent from 1980 to 1990. However, the track and equipment caused accident rate has leveled off since then.[ii] This implies that breaking past the plateau will require additional resources and/or efficiency improvements of existing approaches for locating and remediating track and equipment defects as soon as they form. Railroads will benefit economically from finding and fixing defects quickly, before they cause derailments or costly delays.

Railroads have been downsizing since 1980 while their operational efficiency improved. They now have fewer than half as many employees per mile of road operated.[iii] At the same time, the rate of traffic growth has been steadily increasing.[iv] Previous studies show that track defects form at a rate that is directly proportional to accumulated trainloads.[v] According to data compiled from the American Association of Railroads (AAR), ton-miles per track-mile have tripled since 1980 as shown in Figure 1. This indicates a widening gap between the rate of defect formation and the labor resources available to discover, diagnose, and fix them. Data from the Surface Transportation Board (STB) shows that Class I railroads currently assign nearly one in four employees to maintenance of way and structures.[vi]

The Federal Track Safety Standards (FTSS) documented in 49 Code of Federal Regulation (CFR) §213.233 defines both the type and frequency of inspections for each track class. These standards require visual inspections at least twice weekly for most track classes in operation. The Federal Railroad Administration (FRA) rigorously enforces these standards and imposes hefty fines for non-compliances. The FRA operates several automated inspection cars containing a variety of non-destructive-evaluation (NDE) technologies to analyze most of the tracks in operation each year.

Railroads augment visual inspections with automated NDE equipment to locate developing and mature defects more quickly. However, the overall inspection rate is practically limited because the trailing repair gang must still be able to schedule track

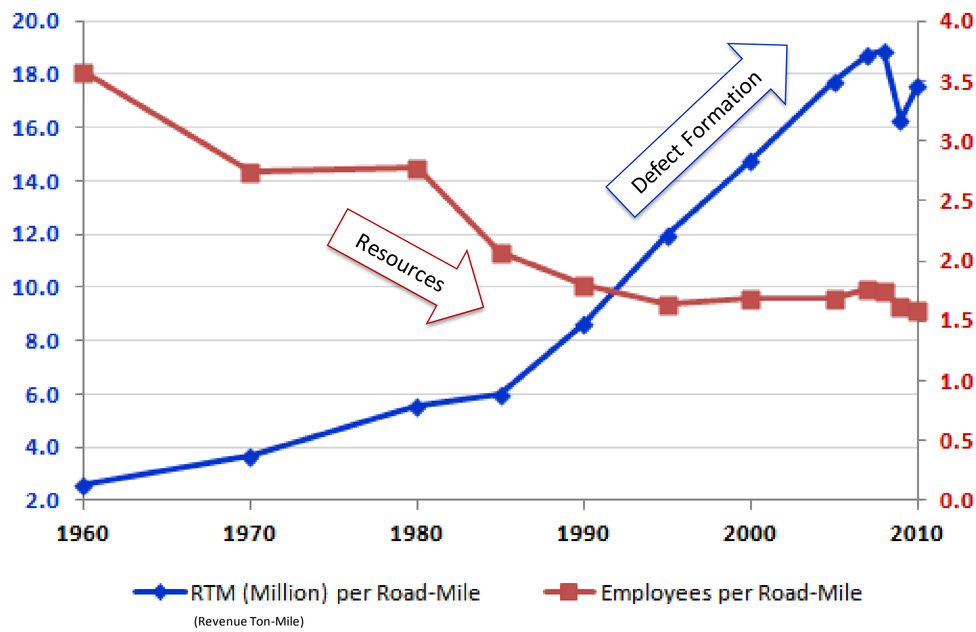


Figure 1: Growth in traffic load relative to employment per mile of road.

time, weather permitting, and keep up with the rate of defect discovery. A recent FRA survey found that railroads conduct 94 percent of the visual inspections with the aid of a Hi-Rail vehicle.[vii] These vehicles contain hydraulic pumps to lower track wheels onto the rail when entering the line and raise them when returning to the pavement. Since many defects are not observable from a Hi-Rail vehicle, inspectors must still patrol the tracks by foot.

Inspections are necessary expenses for preventative maintenance and safety compliance practices, but they also remove track capacity for revenue service. Hi-Rail vehicles are practically limited to speeds between five and thirty miles-per-hour (mph) because inspectors must often stop to verify possible defects. Automated inspection vehicles are three to five times more expensive than freight train locomotives, and the inherent complexities of the NDE technologies they carry limit their speeds. Even though the capabilities of these technologies have improved over the years, they still fall short of average train speeds, and they cannot locate all defects with perfect recognition rates. The FTSS require that inspectors visually verify all defects.

Literature Review of NDE Technologies

Railroads supplement human visual observations with specially outfitted inspection cars that autonomously analyze the track for defects using non-destructive evaluation (NDE) technologies. These include electromagnetic, acoustic, optical, and inertial sensing methods, which this research organizes in the taxonomy of **Error! Reference source not found.**. When deployed on inspection cars, NDE can locate many types of defects, faster and more consistently than most human inspectors can. However, they have significant shortcomings in accuracy, precision, size, and cost, in addition to their high price tag. Moreover, inspection vehicles add non-revenue traffic to the tracks, which decreases available capacity and potentially increases downtime.

Railroads deploy NDE methods in two ways:

1) as infrastructure integrated sensors to monitor the local area infrastructure and passing train characteristics
2) as rolling stock integrated sensors to continuously monitor the traveled infrastructure and vehicle for defects

The latter method is favored by the researchers because of effectiveness. But, the size and

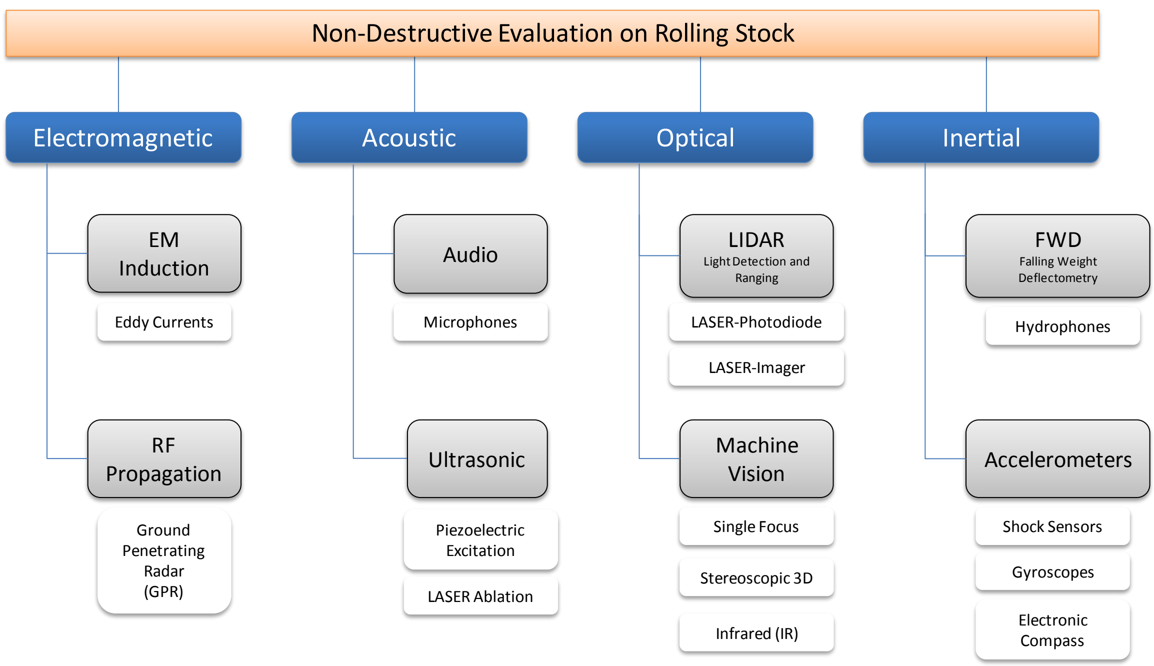


Figure 3: A Taxonomy of NDE technologies.

cost of these technologies currently limit their deployment to specially constructed automated inspection vehicles that locate internal rail flaws, irregular track geometry, track modulus, and gauge restraint. According to §213.233 of the FTSS, railroads must conduct automated track geometry measurements one to three times annually per section of track. Table 1 summarizes the overall FTSS requirements.

Table 1: Summary of Federal Track Safety Standards (49 CFR §213.233)

		Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9
Maximum Operating Speed (mph)	Passenger	15	30	60	80	90	110	125	150	200
	Freight	10	25	40	60	80				
Track Inspection Requirements										
Track Patrol	Visual Inspections (Track)	2 weekly (passenger)	2 weekly						3 weekly	3 weekly
	Visual Inspections (Switch, Crossings)	1 per month					1 per week			
	Functional Inspections (mechanism/rod switches)			1 per 3 month						
AUTOMATED	Load Measuring Wheels						During System Qualification		During System Qualification, Annually	
	Truck Frame Accelerometer						During System Qualification	1 per month	1 per day	
	Carbody Accelerometer						1 per 3 months	1 per month	1 per day	
	Geometry Car							1 per 60 days	1 per 30 days	
	Pilot or Inspection Train								Next train restricted to 100 mph if no operation in 8-hr period.	
	Gage Restraint Measurement System								1 per year	
	Rail Flaw			PSGR MIN(1/40 MGT, 1/yr) No PSGR MIN(1/30 MGT, 1/yr)	MIN(Once per 40 MGT, Once per year)		2 per year			

Passenger Trains Operate MIN(Once per 40 MGT, Once per Year)

No Passenger Trains Operate MIN(Once per 30 MGT, Once per Year)

The FRA believes that "the development of measurement technologies fitted on moving equipment has greatly increased the accuracy and speed of inspections, and has been a major factor in the decline of track-caused derailments."[viii]

All NDE technologies emit some forms of energy into the track area and sense a response. The transmitted energy can be electromagnetic, optical, acoustic, or kinetic. Although some of these technologies have continuously improved over the years, they are still not sufficiently accurate to replace visual inspections. The Amtrak derailment near Flora, Mississippi on April 6, 2004 is a characteristic case study of this shortcoming.[ix] The literature search finds that no single NDE technique offers a complete solution for finding and characterizing all types of defects.

Therefore, all full-scale solutions combine a variety of complementary NDE techniques. This combination further increases their size, complexity, computational, and maintenance requirements.[x] The most constraining technologies of the combined solution limit the inspection speed well below the average revenue-service train speed.[xi] The next few sections examine the functionality and limitations of each type of technology.

Electromagnetic Sensors

Waveforms carrying electromagnetic energy pass through a media, induce eddy currents at the media boundary, or reflect from the media boundary. Probes inject electromagnetic energy into the track area and sensor arrays pick up the reflected energy or induced currents.

Electromagnetic Induction

An alternating current in a coil placed within a few millimeters of the railhead will induce *eddy currents* in the conductive portions of the rail. A second receiver coil monitors the phase and magnitude of these eddy currents to detect changes in the electrical conductivity and magnetic permeability of the material. Rail flaws such as cracks will show up as parameter changes from normal.

Eddy current approaches are one of the earliest NDE methods used. They have the advantage of being able to detect small cracks near the surface of complex shapes such as a rail. However, they cannot analyze non-conductive materials. In fact, the surface finish and standoff distance from the rail affects the reading. Consequently, these probes must travel relatively close to the railhead, with a consistent standoff distance. This requirement practically limits their speed and potential for deployment on revenue service trains.

Radio Wave Propagation

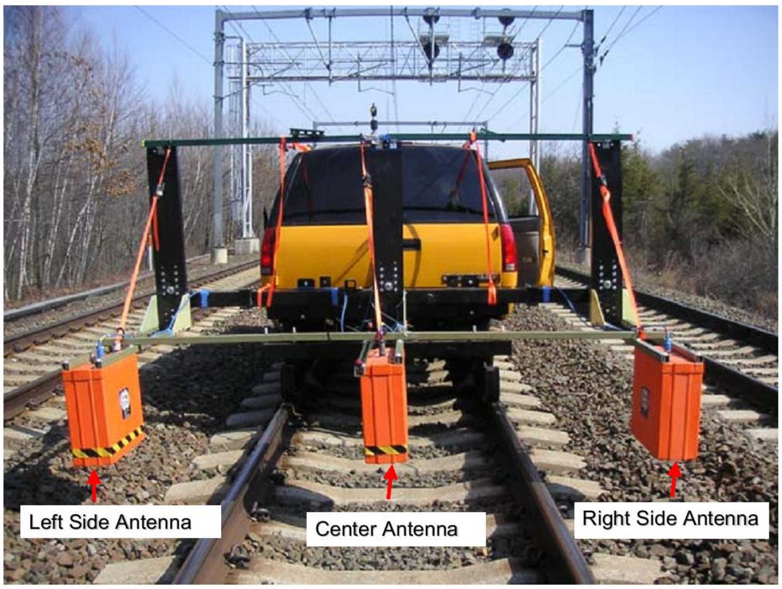
Ground Penetrating Radio Detection and Ranging (RADAR) systems, also known as GPR, provides an interpretation of the load bearing capacity of the underlying track support structure, particularly the ballast, sub-ballast, and sub-grade.[xii] A GPR produces a radiographic image interpretation of the subsurface layers by sending an electromagnetic energy pulse into the ground and observing reflections of the propagating radio waves. Typical GPR frequencies range from 400 MHz to 3 GHz range, depending on depth and resolution of interest. Decades of research in GPR seem to converge on 2 GHz for characterizing the degree of ballast fouling near the surface, and 500 MHz for identifying sub-ballast and sub-grade anomalies to a depth of about 6 feet.

The FCC limits the radio frequency power output at various frequencies. This constrains the convergence time needed for the background noise filters, which practically limits the inspection vehicle speed to about 25 mph. Surveying smaller areas between ties for more detail will constrain the speed to about 8 mph. Reducing the scan depth to a few inches, and quadrupling the antennas and controllers to decrease the scanning area per antenna can push the inspection speed to about 125 mph.[xiii] However, the size of these high directivity antennas are inversely proportional to the radio frequency wavelength and can measure several feet in each dimension as shown in Figure 4. The high output power also requires physically large power supplies and power conditioning circuitry to minimize noise contamination in the faint backscatter signals.

When combined with mechanistic models, GPR data can estimate vertical modulus to predict failures.[xiv] However, as with other NDE techniques such as eddy currents, considerable expertise is necessary to effectively design, conduct, and interpret GPR surveys. High conductivity materials such as clay and salt contaminated soils limit GPR performance. Rocky soils also excessively scatter the signals and reduce the information content. In general, GPR solutions are presently too large, too slow, and too expensive for integration on revenue service trains.

Acoustic Sensors

Audio



Source: Federal Railroad Administration (FRA), 2009

Figure 4: GPR Attachment for a Hi-Rail.

Wheel bearing defects and wheel flats produce acoustic signatures that either wayside or rolling stock microphones can detect. Although they cannot detect all bearing defects, they tend to outperform infrared heat detecting solutions because defective bearings will generate a characteristic acoustic signature much earlier and heat much later in their deterioration cycle. Most commercially available solutions are wayside monitors that sense the acoustics of passing vehicles.[xv] Wayside monitors can be effective in identifying equipment defects but do occasionally miss a few that have actually led to derailments.[xvi] Although considered a well-established inspection technology, on-board devices are almost non-existent, most likely because of their limited capabilities and narrow application focus.

Ultrasonic

Thermal expansion creates longitudinal forces in the rail that promotes fatigue cracking, welding separation, and fretting corrosion in bolt-jointed parts. Compressive stress from thermal contraction can lead to track buckling under dynamic trainloads and velocities. The speed of ultrasonic wave propagation along the track is proportional to such longitudinal rail stresses.[xvii] However, measuring the waveform propagation speed to the desired accuracy requires a sufficiently wide separation between the exciter and receiver, and hence multiple probes.

Most ultrasonic flaw detection applications utilize frequencies between 500 KHz to 10 MHz. At frequencies in the megahertz range, sound energy does not travel efficiently through air or other gasses, but it travels freely through most liquids and solids. Therefore, systems designed for inspection cars use liquid-filled rubber wheels to couple the excitation energy into the rail. However, this approach limits inspection speed to about 40 mph.[xviii] Minor variations in the wheel probe position, water path length, and internal fluid temperature significantly affects wheel probe results. The technique also misses cracks in the rail-web and rail-foot.[xix]

Ultrasonic NDE is a relatively new technology, and there is still much to learn about the behavior of guided waves in complex structures such as railroad tracks. There are also numerous performance limitations. For example, the presence of residual layers from wheel burns can shadow internal defects. The backscattered waveforms require complex signal processing and experts to interpret them. The technique is better suited for flaw detection in the material core and relatively poor at detecting surface or near-surface defects where most of the faults are located. Therefore, most NDE equipment includes electromagnetic probes to compensate for this deficiency.[xx] In addition to the limited testing speed, multiple probe types increases the equipment size and power consumption, making them ill-suited for integration on revenue service trains.

Optical Sensors

Optical systems use light emitters to illuminate the surface and image sensors to capture the reflected light. Some systems use LASER sources to measure the distance from the surface while others use high-powered exotic gas light sources to illuminate the surface for image registration. Environmentally insulated and explosion proof cabinets must protect these devices from the harsh environments, making the construction bulky and expensive.

Light Detection and Ranging (LIDAR)

Variations in track modulus causes dynamic loading which reduces the life of track components. Modulus is the supporting force per unit length of rail per unit of vertical deflection, or simply track stiffness. Lower quality rails, ties, rail joints, ballast, and sub-grade exhibits lower track modulus.xxi Traditional methods to measure modulus require track crew traveling the track to apply known loads with falling-weight-deflectors (FWD) and measuring the resulting deflection.xxii Automated methods use LIDAR to estimate the modulus by measuring the amount of rail displacement from a tangential horizontal plane above the wheel contact point. LIDAR measures the light reflected from a transverse beam of LASER emitted across the travel path to create a surface depth profile. Rotating mirror assemblies move a LASER light spot across the travel surface. A series of lenses focus the reflected light onto position sensitive light detectors (photodiode arrays) that translate the distance from the surface to a proportional electrical signal.

The LASER scanning action produces sufficiently high transversal surface resolution but longitudinal resolution decreases with increasing train speed. The high transversal resolution is an advantage of LIDAR but the limited longitudinal resolution is a major shortcoming. Manufacturers can overcome this limitation, to some degree, by using sophisticated components that increase the scan rate, thereby increasing the inspection speed beyond 40 mph. However, such additional performance requires larger and more expensive construction. Overall, the physical limitations in signal bandwidth, signal-to-noise ratio, sample rate, power consumption, and processing speed ultimately provide diminishing returns in all such optical systems. These systems must also operate relatively close to the tracks and their bulky construction and hardening to withstand the harsh environmental conditions make them less attractive for installation on revenue service trains.

Machine Vision Systems

With the appropriate level of surface illumination, machine vision systems can capture an image and process it to extract features that would identify and characterize fault type and severity. Image feature analysis can identify obvious defects such as missing rail fastener components, rail surface deterioration, cracked ties, broken rails, broken switch points, mud spots, and excessive ballast vegetation. Systems that are more recent add additional cameras to create stereoscopic vision or 3D images for depth information. Adding infrared filters will shift the spectral sensitivity towards longer wavelengths to detect cold wheels, hot wheels, and hot journals. Wheels colder than others can indicate poor brake performance. Relatively hot wheels can indicate skidding or sticking brakes. Hot journals can indicate impending bearing failure or overheating from ceased bearings, which can cause a derailment.

The main advantages of machine vision systems include greater objectivity and consistency than human inspectors. However, they have numerous disadvantages. In general, machine vision solutions require large storage capacity for the images, and ample light source with sun shielding for consistent image quality. Image processing is computationally intensive and often involves self-learning algorithms to detect specific objects in the image frame. High-power Xenon lights or LASERS can improve the lighting condition for a subset of image analysis types, but they add significant cost, bulk, and power consumption. Another shortcoming of car-mounted cameras is that the longitudinal resolution depends on the frame capture rate, which in turn limits the car operating speed. Technology advancements can increase frame rate at higher cost, but their difficulty coping with unusual or unforeseen circumstances such as occlusion from precipitation, leaves, or debris ultimately limits their accuracy.[xxiii] Even at high frame rates, these systems cannot detect faults under conditions of low illumination or line-of-sight obstructions. Most of the systems reported in the literature provided roughly 80 percent detection accuracy for the specific faults they targeted, and even so, those were under conditions of good lighting and reasonably high image resolution.

Inertial Sensors

This general class of NDE relates to systems that measure the impulse response from mechanical energy directed into the track structure.

Falling Weight Deflectometry

Methods of structural capacity estimation in the 1980's used a falling weight deflectometer (FWD) to direct kinetic energy into the track support structure while observing the surface deflections with an impulse response sensor such as a geophone.[xxiv]

An inspection car or Hi-Rail typically hauls a trailer containing the FWD equipment. The test speed is limited by the impulse response duration. With the appropriate signal processing, it is possible to measure the impulse response from the weight of the rolling stock itself to estimate of track modulus.[xxv] Early approaches investigated the possibility of measuring track modulus and lateral alignment with gyroscopic sensors mounted on the bogie.[xxvi] The method based its estimate on the principle that double integration of the acceleration signal produces vertical displacement. However, the offset cancellation and calibration required became impractical. This method still holds promise and could yield better results with adaptive signal processing concepts.

Vehicle-Track Interaction Monitors

Inertial sensors that analyze impulse responses from the vehicle-track interaction are the least developed of all NDE technologies currently in use. The FRA sponsored the development and testing of a GPS-accelerometer based device in 1996 to monitor the vibration of wheel and axle assemblies. ENSCO, Inc. commercialized the technology in 1998 as a Vehicle Track Interaction (VTI) monitor and has since deployed it on about 250 freight and passenger trains in North America and Australia.[xxvii] The installation and processing requirements is complex.

The VTI varies with the type of track irregularity and quality of the rail, tie, ballast, and sub-grade. Testing demonstrated that the system could detect 84 percent of FTSS "exception" conditions by using a neural network to establish the optimum shock-level thresholds.[xxviii] It is otherwise difficult to establish these thresholds analytically or by trial-and-error. Possible shock levels vary widely due to a combination of the specific defect type and the VTI characteristics under variations of carload, configuration, speed, and condition.

Early testing showed that VTI sensors produced a high false positive rate (20 percent) for vehicle suspension faults.[xxix] However, with the appropriate sample rate and signal processing, it should be possible to improve their performance.

Based on the unit design, construction details, and required deployment configuration, an experienced engineer's estimate would be roughly several thousand dollars per VTI sensor, not including installation, configuration, cellular connectivity, or maintenance costs. This high unit cost is likely a significant factor in their limited deployment.

An Alternative Approach Using Low-Cost Sensors

As the literature search showed, the speed, size and cost reduction potential of existing NDE methods is practically limited due to their physical and functional limitations. Railroads are interested in cost-effective automated inspection technologies that are suitable for installation on rolling stock to minimize loss of traffic capacity and to keep up with the projected rate of defect formation.[xxx] Rolling stock inspections would allow inspectors to use available track time more efficiently by reducing search time and attending to the defect backlog that the automated technology discovers. Unfortunately, most NDE technologies currently in use are physically large, require a hefty power supply, all kinds of devices such as electromagnetic and ultrasonic probe arrays, exotic gas lights, optical systems, and on-board antennas, and must withstand harsh environmental conditions as they travel within millimeters of the track. Hence, most NDE technologies in their current embodiment are not suitable for installation on revenue service trains.

On-Board Symptom Sensors

Instead of using NDE technologies and visual inspections to locate all defects, this paper explores a concept for deploying low-cost wireless sensors on-board revenue service trains to localize symptoms of potential defects for prioritized follow-up using appropriate inspection methods. Rolling-stock Automatic In-situ Line Deterioration & Operating Condition Sensing (RAILDOCS) will categorize the type of symptom based on how they affect ride quality. For example, vertical perturbations in ride quality could indicate a track modulus related defect such as a cracked joint, deteriorated tie, fouled ballast, or eroded sub-grade. Similarly, dynamic lateral forces may indicate irregular rail geometry such as buckling, poor gauge restraint, and track misalignment. Symptom sensors integrate micro-electro-mechanical (MEMS), global positioning system (GPS) satellite receivers, wireless communications, and microprocessor technology. Figure shows the architecture of a typical device.

Smart phones are currently the most popular embodiment that includes all of the necessary wireless sensor functionality. Previous generation smart phones are now available for less than $50 online, and they provide suitable platforms to quickly develop and demonstrate the proposed approach. Cost reduced, ruggedized sensors will be RFID tags augmented with MEMS and GPS functionality. Electronic On-Board Recorders (EOBRs) used for logging hours-of-service and other logistics integrate MEMS, GPS, and wireless communications. All of these commercially available devices can host software applications that perform the desired sensing functionality.

The RAILDOCS solution currently in development is cost-effective for deployment on every train car. For example, when integrated into RFID tags with vibration energy harvesting power generators, existing wayside readers can upload the MEMS signature log to a central server for processing. Figure illustrates the overall approach to proactive maintenance at the optimum timing.

Inertial Signature Analysis

Centralized digital signal processing (DSP) algorithms will analyze the entire acceleration signature from multiple sensors and traversals, in both time and frequency

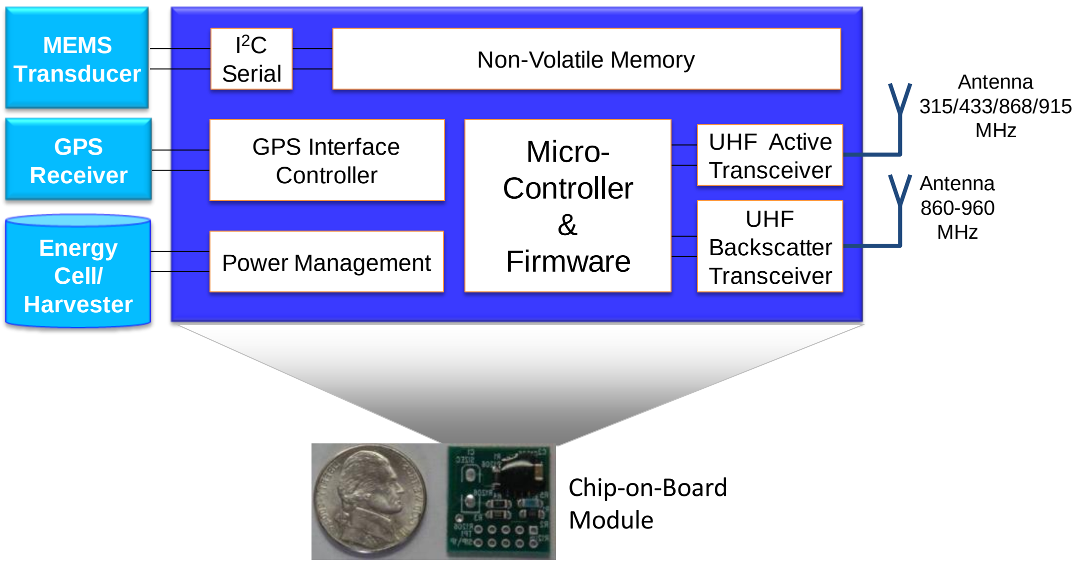


Figure 5: Typical architecture of a sensor based on existing RFID technology.

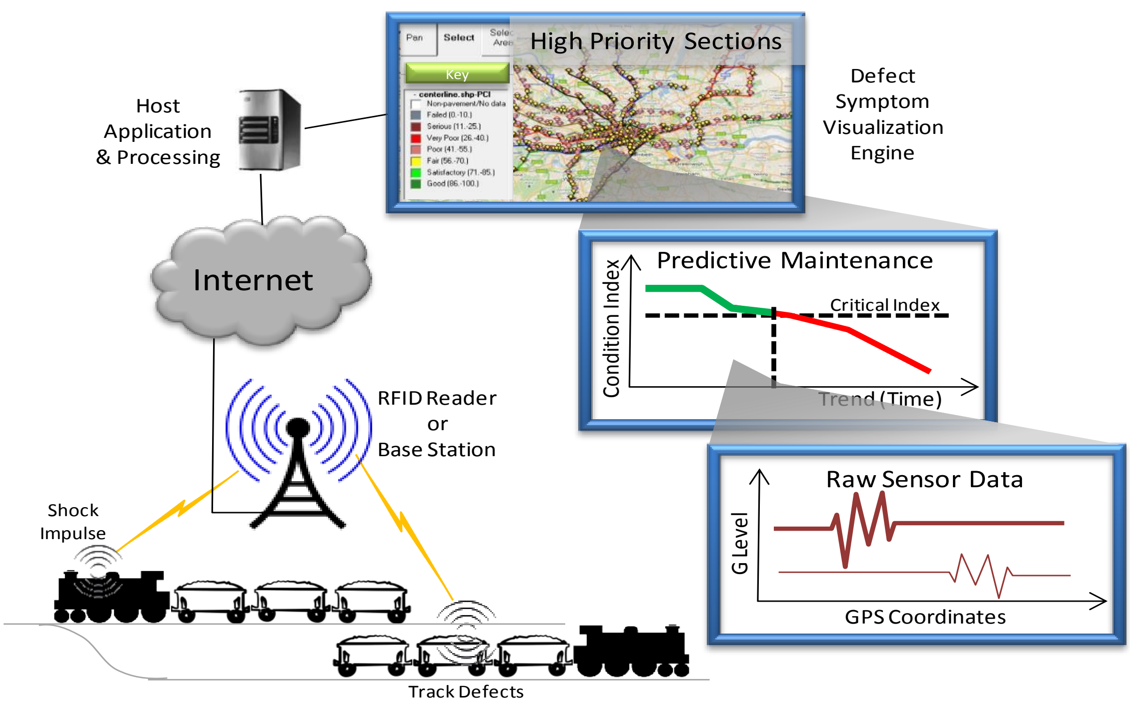


Figure 6: RAILDOCS maintenance system.

domains, to improve both the accuracy and precision of symptom detection and type. For example, given the train speed, a repeating short duration vertical acceleration signature at the same location may indicate a cracked rail or broken rail joint while a longer duration vertical acceleration may be more characteristics of a sunken area due to weakened tie, ballast, or sub-grade support. It is also possible to identify more complex car dynamics by using In-phase/Quadrature (I/Q) diagrams to visualize characteristic impulse responses and periodic motion that result from different track and vehicle defect types. The research team hypothesizes that I/Q techniques borrowed from radio frequency transceiver design theory can provide new insights and analytical capabilities not previously investigated.

The symptom detection accuracy will increase with both the number of sensors deployed, and the number of traversals of a track segment. Repeated sampling with a sensor population over time will tend to average out both MEMS and GPS location errors. The average response from the same sensor population traversing different track segments obviates the need for calibration or neural network based threshold adaption algorithms. The potential for accurately characterizing the type of symptom and perhaps even the type of defect will improve with repeated sampling from multiple sensors. The theory is that signature correlation between sensors will tend to converge with each traversal of a specific track section. In essence, the accuracy and precision will continue to improve with the number of sensor deployment.

Another key advantage of inertial signature DSP is its ability to separate different symptoms from the same signal using frequency spectrum or multi-resolution time-window filters. In addition to signatures from track related defects, the signals will also contain energy from symptoms relating to equipment defects. Track defect symptoms will tend to be location dependent while most equipment related defect symptoms will tend to be periodic with vehicle motion. The latter include vehicle dynamics that can potentially lead to derailments at certain speeds that induce harmonic oscillations from wheel hunting, “rock-and-roll”, “swing-and-sway”, “pitch and bounce”, and “yaw and sway” motion. Repeating impact impulses and vibration levels can be a symptom of wheel flats, sticking brakes, and dragging equipment.[xxxi] The average vehicle condition affects the track deterioration rate.[xxxii] Therefore, this approach will help to identify equipment defects, which when removed and repaired, will extend railroad asset life cycle.

Focused Inspections at Symptom Sites

The RAILDOCS approach aims to optimize the mandatory inspection process by allocating precious track time and resources to prioritized locations where defects are most likely present. RAILDOCS is strictly not a track inspection method, but rather a track and vehicle condition monitoring system to locate symptoms of likely defects for prioritization and further scrutiny, using approved track inspection methods.

As summarized in the literature review, it is evident that no single NDE method excels at locating and characterizing all defect types. Therefore, railroads deploy inspection vehicles that integrate multiple technologies or multiple inspection vehicles with a different NDE and crew specialization.

With advanced knowledge of the location, characteristic, and severity of symptoms, inspectors will be able to arrange for the best technology and/or expertise to diagnose a potentially high-risk defect at that location. This approach focuses existing NDE and technical expertise on prioritized investigations, while maintaining compliance with the

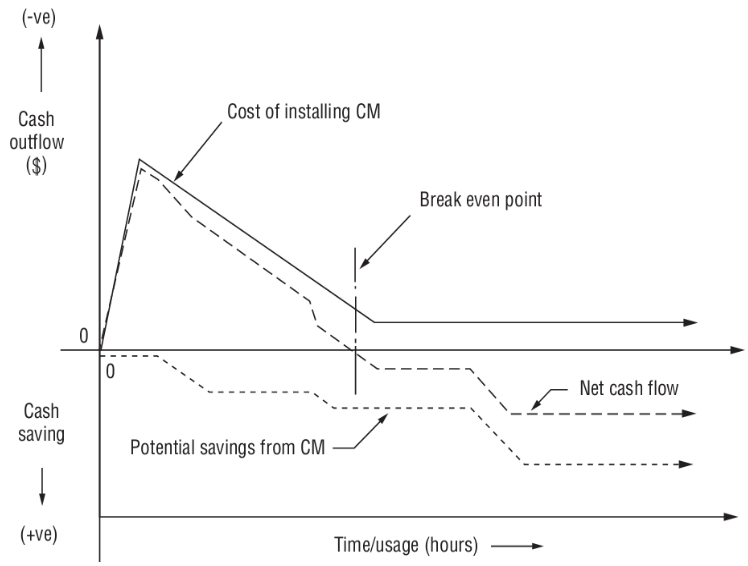


Figure 7: Typical cash flow from an investment in predictive maintenance.

FTSS. Instead of aggressively deploying automated NDE equipment to discover new defect formation as traffic load-density increases, inspectors can focus those specialty technologies on complementary tasks such as internal rail flaw detection, at the more relaxed inspection intervals required for that track class.

Optimized Maintenance

Track performance directly affects a railroad's ability to respond to growing traffic demands by moving heavier carloads at higher speeds. Preventive maintenance programs help railroads maintain track quality and extend asset life but those programs are only as effective as the quantity and quality of conditioning monitoring inputs. Surveys of American production industries indicate that one-third of maintenance cost was unnecessary. Conversely, repairs performed in the "run-to-failure" mode averaged about three times higher than the same repair made within a preventative maintenance mode.[xxxiii] Figure illustrates the net benefits of incorporating a condition monitoring (CM) technology over time. CM technology such as RAILDOCS can provide regular and consistent inputs to a preventative maintenance program and enable a predictive maintenance approach by forecasting maintenance triggers. Inputs from visual and NDE inspections are not as appropriate for long-term predictive maintenance forecasting because the FTSS requires immediate remediation action upon defect discovery. The inputs from automated symptom detection provide a more consistent, long-term indication of the defect formation rate and their progression.

Vehicle Fault Prediction

Studies show that bogie mounted sensors can produce signals that provide an indication of running gear condition and absolute train speed.[xxxiv] They offer an opportunity for more frequent track and vehicle condition monitoring. Longitudinal inertial sensors provide information to estimate train speed and location when GPS signals degrade from loss of direct line-of-sight to the satellites. Non-uniform acceleration and deceleration may indicate traction or braking issues. As previously indicated, the appropriate inertial sensors and signal processing techniques can analyze the vehicle dynamics to detect a variety of dangerous periodic motion that could result in derailment. On-board inertial sensor signals also presents an opportunity for integration with positive train control (PTC) systems to enforce stops, temporary slow orders, and speed limits. They have the potential to provide a "black box" capability for post analysis of train performance or accidents.

Track Quality Index

Early approaches to rate track condition incorporated the opinions of a panel of subject matter experts and trained inspectors. Track managers converted panel ratings of visual flaws into meaningful indices by using various models and weighting schemes.[xxxv] An approach developed in the 1970's incorporated the statistical distribution of track leveling, gauge, distortion, super-elevation, and alignment into a more objective condition index.[xxxvi] Research in the early 1980's discovered that it was possible to formulate a Track Quality Index (TQI) by viewing track geometry as a periodically modulated random process.[xxxvii] Approaches that are more recent combine statistical coefficients from separate track geometry parameters such as gauge, profile, alignment, and twist to produce an overall quality index for a specific track class.[xxxviii]

There currently is no standard for producing a track condition index. Therefore, railroad companies around the world use different approaches. The Australian Rail Track Corporation Ltd. (ARTC) calculates a quality index based on the standard deviation of slope variations for horizontal surface alignment, vertical alignment, twist, and gauge over a 100-meter track section.[xxxix] Chinese railway maintenance departments use a quality index of track irregularity based on averaging slope variations over a 200-meter section of track.[xl]

Ride quality studies in the early 1970's of various passenger transportation modes found that lateral train vibration levels as low as 0.1g acceleration and with frequency components below one Hertz contributes to significant discomfort and could result in motion sickness. This correlation led to an investigation of using vibration measurements as a quantitative index to identify rough track sections for maintenance.[xli] This approach required calibration, and consistency was difficult to achieve. The Swedish Rail Administration subsequently found a high correlation between passenger perceived vibration levels and track condition, even for marginal variations in track quality.[xlii] The FRA found that rougher tracks have longer space curves (or arc lengths) within a fixed straight-line distance.[xliii] Therefore, instead of calculating the statistical deviations of track geometry parameters, the FRA derives a TQI from track roughness measurements across 264 or 528 feet sections by measuring "space-curve" lengths at one-foot intervals. However, experts must calibrate the ride quality instrumentation for each application.[xliv]

This paper defines a track quality index by deriving a track impact factor (TIF) from the overall ride roughness that a MEMS accelerometer reports. When measured from a consistent location and orientation, the TIF will be suitable for incorporation into a deterioration model to forecast optimum maintenance triggers. The TIF is a measure of the amount of combined vertical and lateral energy that the track structure imparts into the vehicle. The resultant g-force magnitude from the MEMS accelerometer is shown in equation 1,

$$g_{res}(t) = \sqrt{g_z(t)^2 + g_y(t)^2} \qquad \text{Eq. 1}$$

where $g_z(t)$ and $g_y(t)$ are the vertical and lateral acceleration component time-signatures respectively. The phase component of these orthogonal time signatures contains valuable information for analyzing vehicle-track interaction, but not the strength of their impact. The signal energy from time 0 to T, provided as a root-mean-square (RMS) value, is essentially the area under its power spectral density (PSD) curve. However, computing the PSD for every track segment signature using Fast Fourier Transforms would be computationally intensive. A novel approach is to use Parseval's Theorem and obtain the signal energy as a time integration of the square magnitude of the signal from time 0 to T,

$$TIF(T) = \sqrt{\int_0^T \left|g_{res}(t)\right|^2 dt} \qquad \text{Eq. 2}$$

However, this assumes that the train is moving at a constant speed $\sigma(t) = \sigma$. Previous work from the PAVVET project provides an approach to speed-normalized the impact factor.[xlv] The resulting discrete-time measure of the impact factor is,

$$TIF(N) = \sqrt{\Delta T \sum_{k=0}^{N-1} \left| \frac{g_{res}(k\Delta T)}{\sigma(k\Delta T)} \right|^2} \qquad \text{Eq. 3}$$

where N is the total number of signal samples for the track segment and ΔT is the sample interval. This factor is directly proportional to the ride roughness from both vertical and lateral disturbances. The quality index of a track segment k is the average TIF over a pre-determined time period p, from sensor i and traversal j,

$$TQI_k(p) = \frac{\sum_{i,j}^{S,J} TIF_{ijk}(p)}{S + J} \qquad \text{Eq. 4}$$

where S and J are the total number of sensors and traversals respectively for the time period p.

Track Deterioration Model

The proposed deterioration model for a track segment k incorporates TQI_k because it directly correlates with the amount of deviation from a uniform and smooth ride. The PAVVET project utilizes a similar approach for pavement condition monitoring, and the model is presently providing good results and correlation with the International Roughness Index (IRI).

One of the deterioration models proposed for investigation will produce the segment TQI as a function of traffic loading L in ton-miles for a segment k and accumulated over a time period p such that,

$$TQI(L_k) = [TQI_0]_k e^{\beta_k L_k} \qquad \text{Eq. 5}$$

The parameter β_k depends on the local environmental conditions and traffic load density for track segment k. Continuous sensing produces the actual TQI, which automatically calibrates the model for β_k to improve its forecasting accuracy. Solving for L_k and establishing the TQI level that triggers maintenance will allow railroads to forecast maintenance cycles based on traffic load projections.

Expected Results and Discussion

The complete RAILDOCS solution will be low-cost and maintenance-free. The remote DSP algorithms will be capable of continuous performance improvements from a centralized location because they operate on the raw sensor data. Sensors will maintain low-cost, low power operation and small size because they will provide the simplest possible functions, namely data logging and opportunistic upload. The remote algorithms will continue to improve in precision and accuracy with the number of sensors deployed and the number of repeating train traversals.

The first hardware prototypes to demonstrate a proof-of-concept will be previous generation smart phones that contain the necessary MEMS, GPS, wireless communications, and memory storage capabilities. These devices are currently available through on-line purchases for less than $50 each. The cost will likely reduce further with the release of newer generation devices. Installation will be as simple as attaching the device to a flat surface in a locomotive or train car and connecting it to a power source. Simpler RFID devices based on vibration energy harvesting will provide a similar functionality but carry their own power source. When ordered in bulk quantities, the enhanced RFID devices should cost less than $20 each.

Algorithms running on a remote server will analyze the streaming symptom sensor signals in real-time and assign signature-analysis results to a geographic information systems (GIS) enabled database. Inspectors in the field will be able to query the database using a browser-based interface, including from mobile devices in the field. This project is developing the algorithm details and techniques to analyze real-time sensor signals for defect symptoms. In addition, the algorithms will combine multiple signal streams to derive a track quality index that enables a preventative maintenance approach. The project will also investigate the accuracy of deterioration forecasting models based on real-time calibration using the continuously updating track quality index.

In summary, overall benefits of the proposed approach are:

- maintenance-free, low-cost sensors for every train
- real-time defect symptom reporting from the actual loaded revenue service trains
- complement for existing inspection methods by focusing their resources more efficiently
- automatically regulate condition monitoring periodicity with train traffic

- reduces NDE inspection vehicle traffic by narrowing their focus to prioritized areas
- enables an optimized maintenance approach that reduces network-wide maintenance cost
- provides real-time train location, speed, car-ordering, schedule, operations, safety related information, and possible integration with PTC solutions

The limitations of this approach are:

- does not completely replace existing NDE and visual inspection methods
- cannot report symptoms of defects that do not affect ride quality
- real-time reporting will be affected by the degree of wireless network coverage
- location accuracy will be affected by the GPS accuracy (but with potential for inertial compass and MEMS correction)

This research introduced a novel approach, leveraging rapid technical advancements in wireless micro-electromechanical (MEMS) sensors, to provide a database of defect symptoms as they form. RFID augmented with MEMS and GPS provide the required sensor functionality. RFID products are sufficiently cost-effective, small, and rugged for installation on every revenue service train. The research team deployed a similar solution for pavement condition monitoring, which is presently delivering excellent results. Deployed sensors continuously sample MEMS accelerometer and GPS signals, and upload their data log whenever a tagged vehicle within range of a preferred wireless connection. Wireless gateway options include RFID reader, Bluetooth, and Wi-Fi hotspots. Sensors can also connect via a cellular network and a bulk subscription service. Remote digital signal processing algorithms will analyze the three-dimensional MEMS signature to identify track and vehicle induced disturbances to ride quality. These include the degree of vertical modulus, lateral alignment and longitudinal motion irregularity, and vehicle-track interaction that result in unstable roll, yaw, and pitch dynamics.

In addition to continuously locating symptoms for prioritization and focused follow-up inspections, the RAILDOCS system will deliver a quantitative and consistent track quality index derived from track-induced components of the ride quality. Sensors in-situ revenue service trains will continuously update the quality index to provide a high-accuracy forecast of the track deterioration rate, and enable an optimized maintenance approach. Other capabilities enabled include real-time train location, speed, headway, system performance, safety monitoring, and PTC system augmentations.

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