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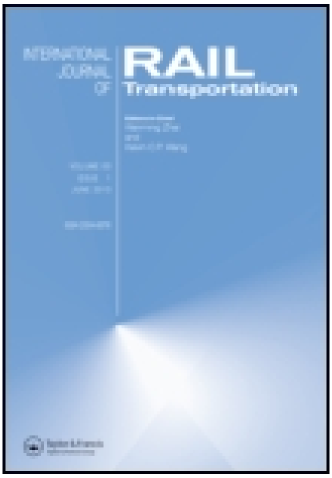

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Beyond mandated track safety inspections using a mission-focused, knowledge-based approach

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The inspection of railroad track is typically mandated by applicable track standards which generally address intent (safety and/or maintenance) and calendar frequency. Likewise, the maintenance and repair (M&R) of track is often compliance-driven with the intent of sustaining the condition requirements associated with a track standards-based track class. This approach falls short of optimising inspections because it is not based on strategic asset management needs. This approach also does not lead to an optimal mix of M&R work activities under varying budget constraints. This paper expands on a "knowledge-based" concept developed for building asset management whereby maintenance inspections are optimally scheduled based on knowledge of the asset and not the calendar. Included is the introduction of a "mission-focused" scoring metric that measures track segment importance. This track priority score along with other readily attainable track condition metrics form the basis for developing a knowledge-based optimised inspection plan. While the discussion in this paper focuses on military railroad track asset management, the process is directly applicable to the entire small railroad niche (military, shortlines and industrials) due to the specific metrics used. Discussion beyond military trackage is provided to demonstrate this application. The concept, however, has even broader implications throughout the industry (Class Is, regionals, transits, etc.). Finally, the paper addresses research into a framework for incorporating mission and other information to develop knowledge-based optimised M&R plans.

Keywords: track inspection; knowledge-based; KBI; condition index; RAILER; mission-focused

1. Introduction

Freight railroads serve a vital interest to the US economy and its defence. These railroad networks serve a variety of purposes, delivering raw materials to producers, finished goods to markets and even transporting munitions, supplies, fuels and equipment between military installations and ports. The critical nature of the track infrastructure requires that sound asset management principles be applied to ensure readiness and reliability of the system, because a failure or disruption at any given point in the network can cause costly delays, jeopardise safety and necessitate recovery and repair.

Railroad track asset management is founded on many of the elements that define asset management programmes for other civil infrastructure domains, such as roads, bridges, pipelines and buildings. This includes, in large part, the following: (1) an inventory of the

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*Corresponding author. Email: uzarski@illinois.edu systems and components that make up the network, (2) an inspection of those components to collect observations about the condition and performance of the network, (3) a process to measure the current state of the assets through condition and performance indicators based on inspection observations, (4) a methodology to predict the change in performance indicators for future points in time and (5) an identification of work activities based on applicable standards, managerial policies and priorities and available budgets.

The demands of modern large scale, high tonnage, relatively high speed railroading dictate reliable track infrastructure. To meet that managerial challenge, the Class I railroads in the United States embrace track asset management in a systematic, but customised way because each Class I railroad has unique operational needs and cultural management styles. These track asset management "systems" may serve the Class I community well, but they are not always scalable or applicable to the over 150 military, 500 shortline and numerous industrial rail networks in the United States who have varying and diverse track structures, operational tempos, traffic volumes, resources and maintenance policies. To provide a track asset management solution for these situations, the US Army Corps of Engineers developed the RAILER® Sustainment Management System (SMS) [1] to help decision-makers manage the operational maintenance expenses and capital investments for military railroad track repair and upgrades. The RAILER® system is a computer-based application which includes all the asset management elements discussed above, but is flexible enough to support a network with many miles of track, or one with as little as several hundred feet [2]. Designed for the small freight railroad niche, RAILER® software is available "off-the-shelf" for the civilian shortline and industrial railroad community. RAILER® stores track structure information and condition-related defects, performs condition assessments and identifies track maintenance, repair and rehabilitation requirements. The RAILER® system employs a structured method for delineating the aspects of a complex railroad network into manageable individual tracks and segments for better management, as well as a standardised inspection process with subsequent condition reporting and maintenance and repair (M&R) requirements. The system processes and reports tactical information at a local level, but can also aggregate information to a regional or headquarters level for strategic decision-making.

The federal government owns or manages, in part, over 900,000 buildings and structures, thousands of miles of roadways and utilities and hundreds of miles of railroad track [3]. This huge portfolio, parsed over hundreds of installations and/or locations, poses significant asset management challenges. In response to that challenge, the US Army Corps of Engineers also developed a "knowledge-based" approach to building facility inspection and overall asset management. This knowledge-based approach does away with usual calendar-based (e.g. annual) inspection scheduling and a standard deficiency-type inspection (the discovery and recording of defects or deficiencies that warrant correction) [4] with one that approaches inspection intensity on a tiered basis and schedules those inspections based on a series of metrics [5,6]. This knowledge-based approach has been endorsed and recommended for widespread application by the National Research Council (NRC) [7]. Inasmuch as buildings dominate the federal infrastructure portfolio, the knowledge-based approach has been primarily focused on building components.

The purpose of this paper is to demonstrate how a knowledge-based approach can be expanded to include railroad track inspection and later to improve M&R decision-making. The focus is on military Department of Defense (DoD) trackage, but the knowledge-based approach described in this paper can be easily applied to the civilian shortline and industrial railroad niche, as well. As such, the discussion is expanded, where appropriate, to demonstrate that application.

2. Current DoD track asset management practices

2.1. *Military track asset management challenge*

Out of the entire federal government's asset portfolio, the DoD operates and maintains just over 3000 linear miles of active railroad track, making its total size between that of the largest regional railroad and the smallest Class I. However, whereas the regionals and Class Is are primarily comprised of continuous rail lines, the DoD track is comprised of over 150 geographically dispersed networks located across military installations worldwide, which makes it comparable to major shortline holding companies. The scale, complexity and usage of these networks vary greatly from installation to installation, making track asset management a challenge. Due to these reasons, the implementation of universal track standards, regular inspections, and an objective, but common condition assessment approach and metrics are of critical importance to track asset management practices.

2.2. *RAILER® usage*

As mentioned above, the scale, complexity and usage of military track networks vary greatly among geographic locations, making a common asset management approach a challenge. For the DoD, the RAILER® system has been implemented to overcome this challenge, by providing a common knowledge-based platform for collecting and storing relevant track information.

The Office of the Secretary of Defense (OSD) requires that all DoD Services report on their real property assets at each installation. To streamline information across the military and to better support enterprise analysis capabilities, Real Property Inventory Requirements (RPIR) have been established to consistently collect and record the pertinent data about linear structure segments and nodes. For DoD railroad track assets, OSD has adopted the use of the RAILER® business rules to segment the installation track network and report characteristic track inventory information. This methodology and data structure is used for RPIR implementation for railroad track assets to provide a consistent approach to asset inventory data collection.

RAILER® incorporates the track standards, track inspection, condition assessment and M&R planning features discussed below.

2.3. *Track standards*

Track standards are a fundamental staple to railroad track engineering in the United States and elsewhere in the world. Track standards fall into three categories: design/construction, maintenance and safety. Track asset management incorporates the usage of each of these standards either though public law or prudent management policy.

In the United States, the most relevant set of standards is the Federal Railroad Administration (FRA) Track Safety Standards [8] implemented through US Code of Federal Regulations, Title 49, Part 213 (49 CFR2 13). These standards are germane to "…standard gauge track in the general railroad system of transportation" [8], meaning track in commercial service. Excluded is track located within an installation which is not part of the general railroad system of transportation (e.g. military installation) and track used in rapid transit operations in urban areas also not connected to the general railroad transportation system. As the title implies, the FRA Track Safety Standards are focused on public safety. The standards establish track classes with a maximum speed per class. Then, based on track class, the standards address, in part, inspection frequency, how inspections may be conducted and condition requirements for a given class. Track not meeting the requirements of a given class are reclassified to an applicable lower class (and lower maximum speed) until all of the requirements of the desired class are met.

The development and usage of maintenance standards, unlike the FRA Safety Standards, are left to the discretion of the railroad owner, including public agency-owned railroads. There is no force of law present to implement these, but prudent management should embrace the concept. Simply put, maintenance standards set condition triggers above those set by the safety standards. When inspection reveals conditions (i.e. track defects) that fall below the maintenance standards, M&R work should be scheduled to raise the track condition. With maintenance standards in place (tailored appropriately for the given railroad) and acted upon, track should rarely run afoul of the safety standards and thus the requirements of the desired track class will be fulfilled. Reclassification to a lower track class and lower speed (e.g. slow order) will rarely occur. Unfortunately, the development and implementation of maintenance standards are not universally embraced, especially in the shortline and industrial railroad community.

Design/construction standards represent the criteria to which the track is designed and constructed. This will include dimensional criteria, materials, allowed tolerances and overall quality. For tracks in active use, the design/construction standard cannot be upheld indefinitely because the passage of trains and other factors cause track degradation. Thus, properly maintained track should have a condition between the design/construction standard and the maintenance standard. Whether or not track (immediate post-maintenance or repair) is at the design/construction standard is a matter of management policy. Capital renewed track may or may not be brought back to the design/construction standard depending on the extent of the renewal.

As stated above, the FRA Safety Standards are not applicable to military installations. However, this is not to say that the DoD does not embrace the concept. The DoD has developed a set of combined maintenance and safety standards [9]. These standards incorporate elements of the FRA standards by reference.

It is important to note that some railroads operate with a lack of track safety or maintenance standards. These are railroads exempt from the FRA Safety Standards (see above) and who have also not developed maintenance standards. Railroads that may fall into this category are industrial railroads.

2.4. *Track inspection*

The intent of a safety inspection is to catch serious defects as defined in the standards as applicable for the track class. To reduce derailment risk, any serious (or possibly combinations of non-serious) defects found within a particular track segment will result in an appropriate operating restriction being imposed (i.e. slow order, remove from service, or designate as “excepted”), repair being initiated or both. Restrictions may be issued based on either the requirements of the standards or inspector judgement. Inspectors may not ignore the basic requirements of the standards, but an inspector may also impose a more severe restriction or impose a restriction not warranted by the standards due to the situation. Also, a track segment may already be restricted based on previous inspection findings and any new defects found may result in a more severe restriction. Specific repairs may be driven by the requirements of the standards, M&R policy and the desire to remove the restriction or not.

Whereas safety inspections focus on serious defects associated with track class that typically requires prompt corrective action, detailed track inspections focus on a broader range of non-serious defects that left unattended could morph into serious defects, identify work needs as part of a broader maintenance plan and budgeting and provide complete data for condition assessment and degradation rate determination. It should be noted that a detailed track inspection will also serve the purpose of a safety inspection because any serious defect found will be addressed in the same manner as if found during a safety inspection. On the other hand, the superfluous nature of a safety inspection does not provide the necessary granularity needed to meet the purposes of a detailed track inspection.

Inspection requirements are driven by the track standards. From a safety perspective, the FRA requires an inspection frequency ranging from twice weekly to monthly depending on the track class [8]. The inspections, themselves, are superficial. Inspectors may inspect on foot or from a moving vehicle over the track and under certain circumstances up to four tracks may be inspected at once [8].

Maintenance standards should also recognise that additional inspection effort (more detail and possibly in addition to the safety frequency) will likely be needed. A frequency should be established in the standard and/or should be coordinated with the M&R planning cycle. This inspection could be scheduled in conjunction with a routine safety inspection. Unfortunately, since maintenance standards are lacking for many railroads, detailed track inspections may also be lacking, except on an “as needed” basis (generally in conjunction with a project – planned or emergency).

The DoD addresses both safety and detailed track inspections within their standards. Safety inspections range from weekly to semi-annual depending on track category (based on type and use) and traffic frequency [9]. Detailed track inspections for all track categories are to be performed annually [9]. Both types of inspections are often conducted on foot, but hi-rail vehicles may be employed for the safety inspections.

Railroads with no track standards may also have no formal inspection programme. Inspections (of some form) may be conducted “ad hoc” or on an “as needed” basis.

Continuous operator inspections (a form of safety inspection), preventive maintenance inspections performed in conjunction with performing preventive maintenance (a form of maintenance inspection), special inspections (e.g. post-flooding event), detailed project-level inspections associated with a given project and quality control inspections (post-work) are all present and important to the overall scheme of track asset management, but are not within the scope of this paper.

2.5. *Condition assessment*

As stated above, an assessment of track condition is one of the purposes for conducting a track inspection. Condition assessment, in a broad sense, provides for an analysis of inspection data to ascertain the ability of a track, track segment and overall network to perform as required. This ability, or lack thereof, leads to a determination and prioritisation of work needs, budget formulation and determination of the effectiveness of the work. There are limited approaches and metrics available for measuring condition. These include track standard condition levels and condition indexes.

2.5.1. *Track standard condition levels*

The most common metric for measuring track condition is the condition levels associated with the applicable track standards. As discussed above, DoD trackage consists of various individual track networks, each associated with a given installation. Each network is a collection of individual tracks and each track is divided into logical track segments [10]. Track standards condition is applied on a track segment by track segment basis. Depending on the defects found during an inspection, the track segment will be assessed at Full Compliance, Restricted Operations (10 mile/hour maximum speed) and No Operations [9]. These condition levels address the safety standard portion of the DoD track standards. Also, condition categories A and B are applied to assess condition based on the maintenance standard portion of the DoD track standards. Such condition levels (as are the FRA Safety Standards track class condition levels) represent a compliance metric, because the track segment is either in compliance with the track standard desired condition level or it is not. Unfortunately, such compliance metrics are only meaningful to the track segment to which they are assessed. Clearly, there is no meaningful way to "roll up" these condition levels to assess condition of a multi-segment track or the network as a whole or determine degradation rates.

2.5.2. *Condition indexes*

Condition indexes were developed by the US Army Corps of Engineers to overcome the limitations of the track standards condition levels in order to fully support the wide range of facility asset management needs, including determining and prioritising current and long-range M&R needs, formulating budgets and measuring the effectiveness of M&R [11]. These condition indexes are intended to reflect the physical ability to support the intended traffic and M&R needs to sustain that traffic [11]. The condition indexes were developed to meet the needs of the US military (low speed – less than 40 mile/hour; low volume – less than 10 MGT/year), but they are applicable to all railroads meeting that criteria including most shortlines and industrial railroads.

There are four different condition indexes and all range in the scale from 0 to 100 (100 is the best possible condition). There is one each for the three major track component groups: rail, joints and fastenings (RJCI), ties (TCI) and ballast and subgrade (BSCI). Inasmuch as M&R tasks are often accomplished along the major track component lines, the various condition indexes directly serve M&R planning and budgeting needs as well as measuring M&R effectiveness. The 0–100 scale is divided into intervals. Each interval has a condition description and indicates the extent of the M&R needed [11]. The fourth index is an overall track structure condition index (TSCI), which represents a weighted average of the other three.

All of the condition indexes are determined through the detailed inspection process [12]. A safety inspection, inasmuch as only serious defects are recorded, does not result in an index computation. However, if detailed inspections are used to establish a baseline or "reset" the condition indexes, the safety inspection results can be used to modify an index by adding any defects found to those previously identified from the detailed inspection. The same modification results when M&R is completed, resulting in previously identified defects being removed from the detailed inspection.

2.6. ***M&R planning and execution***

The track standard operating restrictions and defect findings that result from the rail inspection process are used to identify M&R work requirements for planning and execution. This is accomplished in a systematic process by linking the inspection defects to local work action repairs through an M&R policy. The policy allows asset managers to establish specific guidance on how a defect is addressed, providing a common level of service across a maintenance organisation. An example is the serious defect "All joint ties (sleepers) defective (two-ties)". The M&R policy for this defect may be to "Replace one tie". An alternative policy might be to "Replace two ties". A "Do nothing" alternative is not valid if the desire is to remove the restriction associated with the defect. The choice of replacing one or two ties resides with management and is often budget driven. Limited budgets force M&R to often be "compliance-driven" with work generally limited to rectifying those defects that impose restrictions as per the track standards.

As discussed above, a detailed inspection is likely to turn up many "Full Compliance" (non-serious) defects that do not impose restrictions, but still affect the general condition of the track. While the correction of all identified defects on a track network is usually cost prohibitive and unnecessary, it is typically in an organisation's best interest to address at least a portion of these non-serious defects to proactively prevent future interruptions and costly repairs later on. Again, these non-serious defects may or may not be corrected as per the M&R policy and/or the maintenance standards (if one exists). An example is a three-in-a-row defective tie cluster (not at a joint). The DoD track standards flag this as the maximum-sized allowable cluster as per maintenance, but the cluster size must be four or more in a row to trigger an operating restriction [9]. The applicable M&R policies could be to replace one, two or all three ties. The choice is again typically budget driven. Additionally, a two-in-a-row defective tie cluster is a defect that will not trigger M&R based on the DoD standards, but may still be corrected as per an M&R policy. In this case, the M&R policies may be replaced by one or two ties, or none at all (do nothing).

The work actions proscribed to correct specific defects (serious and non-serious) are considered local work actions. In addition to these, global work actions can also be applied to a segment or portion of the track network to accomplish general maintenance, component restoration or overall track rehabilitation. For example, if a track segment is in major disrepair (as measured by low condition indexes), it may be more cost-effective to perform global track rehabilitation instead of correcting individual defects through local work actions.

Ideally, an optimised work plan for a rail network will usually consider a mix of local and global work actions. The need to correct serious defects should be minimal because planned M&R will minimise the occurrence of serious defects. Finally, an asset management goal should be to attain a desired track condition that minimises overall M&R costs over time.

2.7. *Lack of optimisation for inspection and M&R*

As discussed above, track inspection (safety and detailed) are calendar-driven events. However, the annual requirement for detailed track inspection is less than optimal because track usage, rates of degradation, condition and mission are not considered. Furthermore, the inspection results tend to be used to support compliance-driven M&R rather than optimal M&R. Thus, detailed inspections are often performed whether they are needed or not. As discussed above, railroads without maintenance standards or worse, without any standards, may rarely have detailed inspections performed and thus the necessary information to support optimal M&R is lacking. Unnecessary inspections also cost money that could, perhaps, be better spent elsewhere. Likewise, a lack of inspection also costs money through the penalty cost incurred with "ad hoc" or delayed M&R planning and execution [6].

Within DoD, most track M&R is primarily compliance-driven in accordance with both the safety and maintenance aspects of the track standards. The outcomes of the safety and detailed inspections result in work plans that ensure that the track meets all of the requirements of the track standards. Specific defect correction is addressed though the establishment of budget-related M&R policies. Likewise, railroads without a maintenance standard or any standard are left with limited M&R options. Certainly, the track must be maintained to the minimum compliance requirements of the FRA Safety Standards, if applicable. But, eventually the major components (ties, ballast, etc.) will require significant and costly rehabilitation. Rarely is there an attempt to optimise M&R within the DoD, shortline and industrial railroad community

3. Improved mission-focused methodology

3.1. *Mission-focused scoring of track segments and turnouts*

Any attempt to implement "knowledge-based" principles must consider traffic volume, the operational mission(s) of the various tracks in the track network and the redundancy and efficiency of each route. These are all used to calculate a total priority score (TPS) for each track segment and turnout. An example analysis is provided below.

Figure 1 shows an example track schematic for a portion of a simplified network consisting of five tracks, T1–T5, along with track segments and turnout locations labelled and segment lengths annotated.

3.1.1. *Normalised traffic score*

A traffic analysis measures the number of annual movements across each segment or turnout. These movements could be based on the past year or what is expected in the upcoming year. Each movement is categorised as a hazardous material (HazMat) or non-HazMat movement, depending on the classification of the material being transported. A HazMat multiplier is applied to the HazMat movement measurement, to determine the equivalent number of movements for each track segment and turnout, which is provided in the equation below.

$$\text{EquivalentMove}s_i = \text{Non-HazMatMove}_i + \text{HazMatMultiplier} \times \text{HazMatMove}s_i \tag{1}$$

For this analysis, the HazMatMultiplier is assumed to be 2, meaning HazMat movements receive twice as much traffic importance weight as non-HazMat movements. Of course, since the purpose of assigning a multiplier is for helping to establish track segment importance, the value to be used would be left to management discretion. Also, different hazardous materials could have different multipliers, if desired.

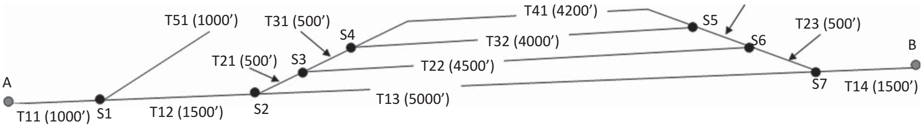

Figure 1. Example track schematic.

Table 1. Traffic analysis to compute normalised traffic score (NTS).

Track segment/ turnout	Length (ft)	Non-HazMat movements	HazMat movements	Equivalent movements	Normalised traffic score
T11	1000	650	312	1274	0.980
T12	1500	572	312	1196	0.920
T13	5000	338	312	962	0.740
T14	1500	390	312	1014	0.780
T21	500	234		234	0.180
T22	4500	104		104	0.080
T23	500	78		78	0.060
T31	500	156		156	0.120
T32	4000	104		104	0.080
T33	500	52		52	0.040
T41	4200	104		104	0.080
T51	1000	104		104	0.080
S1	–	676	312	1300	1.000
S2	–	572	312	1196	0.920
S3	–	234		234	0.180
S4	–	156		156	0.120
S5	–	52		52	0.040
S6	–	78		78	0.060
S7	–	416	312	1040	0.800
Total	24,700	5070	2184	9438	

The normalised traffic score (NTS) is computed for each track segment and turnout by dividing the Equivalent Movements for each by the maximum Equivalent Movements values of all segments and switches in the network. Example traffic data and the NTS for the Figure 1 track segments and turnouts are provided in Table 1.

3.1.2. *Total mission score*

The NTS considers traffic movements, but does not consider mission use or route redundancies. To incorporate these considerations into an overall track segment prioritisation scheme, a mission-based route analysis is also proposed. Based on the analysis of the traffic and a study of the primary missions performed by train crews, the simplified track network shown in Figure 1 supports three missions: (1) car loading/unloading for a container yard (not shown) to the right of point B, which requires access between points A and B, (2) car storage on the long middle segments, T13, T22, T32 and T41 and (3) access to the locomotive service facility at the end of single segment stub track, T51. For track access between points A and B to support the loading mission, the traffic is assumed to be balanced in both directions. However, for the car storage and locomotive servicing missions, traffic is unbalanced in this example, with the predominant origination of traffic from point A (west to east), which occurs 75% of the time, while the remaining 25% of movements originate from point B (east to west).

It should be noted that the DoD track networks exist to support the missions cited above. Industrial railroads would most often be similar. Shortlines, on the other hand, could also support passenger operations, yard operations, an access mission whereby trains (or portions thereof) are received from another railroad and "passed through" to another railroad, or other missions as defined by a particular railroad. The DoD network missions should not be confused with DoD track segment uses which include loading, storage, service (e.g. car repair, locomotive servicing), access (connections to other track segments) and auxiliary (passing sidings, wye tracks and run-around tracks) [10].

The various missions are not necessarily equally important. Organisational leaders need to weight and normalise these using appropriate methods for doing so. A discussion of these methods (e.g. analytical hierarchy) is beyond the scope of this paper. However, for the continuing example used herein, the weighting factors are given as 0.6 for loading, 0.3 for storage and 0.1 for service.

Analysing the potential routes available to perform each mission, one can calculate the amount of track feet and number of turnouts traversed for each route, to measure the efficiency of each route. In addition, one can determine the number of routes to which a particular track segment or turnout is associated. The more routes that a segment is associated, the more critical it is to mission, and the higher its mission rating should be for inspection and M&R.

Table 2 shows the calculation of the route scores for the "Loading" mission. The table lists the track segments and turnouts traversed, for each of four potential routes from each origination point. The length of each route and number of segments is also calculated. Since operating personnel prefer routes with the shortest distance and least number of turnouts traversed, each route is weighted equally based on these two factors.

The segment score (SS) is calculated as follows:

$$\mathrm{SS} = \frac{\frac{\sum x_i}{x_i}}{\sum \frac{\sum x_i}{x_i}} \tag{2}$$

where x_i = the length of route i and i = the route number for each mission.

Table 2. Route scores for loading mission.

Origin point	Track segment	Turnout	Route length (ft)	Number turnout	Segment score	Node score	Route score
A	T11, T12, T13, T14	S1, S2, S7	9000	3	0.268	0.407	0.338
A	T11, T12, T21, T22, T23, T14	S1, S2, S3, S6, S7	9500	5	0.254	0.244	0.249
A	T11, T12, T21, T31, T32, T33, T23, T14	S1, S2, S3, S4, S5, S6, S7	10,000	7	0.241	0.174	0.208
A	T11, T12, T21, T31, T41, T33, T23, T14	S1, S2, S3, S4, S5, S6, S7	10,200	7	0.237	0.174	0.205
B	T14, T13, T12, T11	S7, S2, S1	9000	3	0.268	0.407	0.338
B	T14, T23, T22, T21, T12, T11	S7, S6, S3, S2, S1	9500	5	0.254	0.244	0.249
B	T14, T23, T33, T32, T31, T21, T21, T11	S7, S6, S5, S4, S3, S2, S1	10,000	7	0.241	0.174	0.208
B	T14, T23, T33, T41, T31, T21, T12, T11	S7, S6, S5, S4, S3, S2, S1	10,200	7	0.237	0.174	0.205

Table 3. Route scores for storage mission.

Origin point	Track segment	Turnout	Route length (ft)	Number turnout	Segment score	Node score	Route score
A	T11, T12, T13	S1, S2	7500	2	0.252	0.375	0.313
A	T11, T12, T21, T22	S1, S2, S3	7500	3	0.252	0.250	0.251
A	T11, T12, T21, T31, T32	S1, S2, S3, S4	7500	4	0.252	0.188	0.220
A	T11, T12, T21, T31, T41	S1, S2, S3, S4	7700	4	0.245	0.188	0.216
B	T14, T13	S7	6500	1	0.252	0.462	0.357
B	T14, T23, T22	S7, S6	6500	2	0.252	0.231	0.241
B	T14, T23, T33, T32	S7, S6, S5	6500	3	0.252	0.154	0.203
B	T14, T23, T33, T41	S7, S6, S5	6700	3	0.244	0.154	0.199

The node (turnout) score (NS) is similarly calculated as follows:

$$\mathrm{NS} = \frac{\frac{\sum y_i}{y_i}}{\sum \frac{\sum y_i}{y_i}} \tag{3}$$

where y_i = the number of turnouts traversed in each route.

The route score (RS) is simply the average of the SS and NS for each route, since segment score and node score are weighted equally.

The route analysis discussed above is similarly displayed in Table 3 for the car "Storage" mission and Table 4 for the "Service" mission.

To calculate the mission score for the track segments and turnouts, each mission and each route origination is analysed independently, as shown in Table 5. For a given segment or turnout, the route score calculated above is summed if the element is present in that route. For example, referring to the "Loading" mission originating from point A, segment T11 (see Figure 1) is present in all four potential routes, so its sum is equal to 1. The mission score for a segment or node element is the sum in each direction multiplied by its origination percentage, all multiplied by the mission weighting factor, calculated as follows:

Table 4. Route scores for service mission.

Origin point	Track segment	Turnout	Route length	Number turnout	Segment score	Node score	Route score
A	T11, T51	S1	2000	1	1.000	1.000	1.000
B	T14, T13, T12, T11, T51	S7, S2, S1, S1	10,000	3	0.266	0.444	0.355
B	T14, T23, T22, T21, T12, T11, T51	S7, S6, S3, S2, S1, S1	10,500	6	0.254	0.222	0.237
B	T14, T23, T33, T32, T31, T21, T12, T11, T51	S7, S6, S5, S4, S3, S2, S1, S1	11,000	8	0.242	0.167	0.204
B	T14, T23, T33, T41, T31, T21, T12, T11, T51	S7, S6, S5, S4, S3, S2, S1, S1	11,200	8	0.238	0.167	0.202

Table 5. Total mission score calculation.

	Loading mission (0.6)			Storage mission (0.3)			Service mission (0.1)			
Segment/ node	Point A (0.5)	Point B (0.5)	Mission score	Point A (0.75)	Point B (0.25)	Mission score	Point A (0.75)	Point B (0.25)	Mission score	Total mission score
T11	1	1	0.6	1	0	0.225	1	1	0.1	0.925
T12	1	1	0.6	1	0	0.225	0	1	0.025	0.85
T13	0.338	0.338	0.203	0.313	0.357	0.097	0	0.355	0.009	0.308
T14	1	1	0.6	0	1	0.075	0	1	0.025	0.7
T21	0.662	0.662	0.397	0.687	0	0.155	0	0.645	0.016	0.567
T22	0.249	0.249	0.149	0.251	0.241	0.075	0	0.238	0.006	0.229
T23	0.662	0.662	0.397	0	0.643	0.048	0	0.645	0.016	0.461
T31	0.413	0.413	0.248	0.436	0	0.098	0	0.407	0.01	0.356
T32	0.208	0.208	0.125	0.22	0.203	0.065	0	0.204	0.005	0.194
T33	0.413	0.413	0.248	0	0.402	0.03	0	0.407	0.01	0.288
T41	0.205	0.205	0.123	0.216	0.199	0.064	0	0.202	0.005	0.191
T51	0	0	0	0	0	0	1	1	0.1	0.1
S1	1	1	0.6	1	0	0.225	1	1	0.1	0.925
S2	1	1	0.6	1	0	0.225	0	1	0.025	0.85
S3	0.662	0.662	0.397	0.687	0	0.155	0	0.645	0.016	0.567
S4	0.413	0.413	0.248	0.436	0	0.098	0	0.407	0.01	0.356
S5	0.413	0.413	0.248	0	0.402	0.03	0	0.407	0.01	0.288
S6	0.662	0.662	0.397	0	0.643	0.048	0	0.645	0.016	0.461
S7	1	1	0.6	0	1	0.075	0	1	0.025	0.7

$$\mathrm{MS}_j = \mathrm{MW}_k \times \left(\mathrm{OW}_A \times \sum_{\text{if} j \text{ is in } i} \mathrm{RS}_i + \mathrm{OW}_B \times \sum_{\text{if} j \text{ is in } i} \mathrm{RS}_i \right) \tag{4}$$

where

MS_j = mission score of element j,
MW_k = mission weight of mission k,
OW_A = origination point A percentage,
OW_B = origination point B percentage,
RS_i = route score of route i.

The total mission score (TMS) is the sum of the mission scores across all missions.

$$\mathrm{TMS} = \sum \mathrm{MS}_j \tag{5}$$

3.1.3. *Track priority score*

The track priority score (TPS) is the weighted average of the TMS calculated directly above with the NTS calculated earlier. For this example, each is weighted equally, so the TPS for each segment or turnout is simply the average of the TMS and NTS. Figure 2 shows the aggregate total priority scores annotated on the track schematic map. As is evident from this map, turnouts and track segments without redundant route alternatives display the highest scores, and would be given priority for inspection and in M&R budget allocation.

3.2. *"Knowledge-based" applied to track inspection*

The NRC states that that "knowledge-based" is knowledge (quantifiable information) about a facility's system and component inventory that is used to select the appropriate inspection type and schedule. Thus, inspections are planned and scheduled based on knowledge, not the calendar [7]. In the case of railroad track, a facility is a track segment and components are grouped generally as rail, joints and fastenings; ties (sleepers); and ballast, subgrade and drainage. Turnouts and other special trackwork elements are often considered separate entities; however, inasmuch as they encompass the general components listed above (the condition of which is reflected in the CIs), plus others, and since they are considered part of the track segment within which they reside, turnouts are simply inspected as part of the track segment. Experience within DoD shows this approach to be adequate; however, there may be circumstances (e.g. excessive impact loading) whereby specific special trackwork elements may be "flagged" for separate inspection scheduling

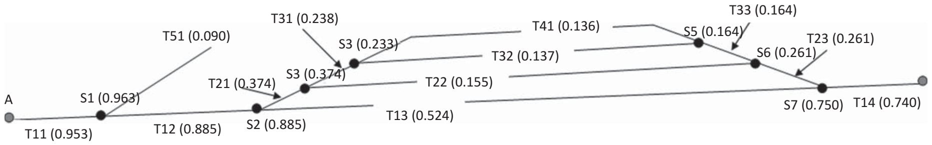

Figure 2. Track network with track priority scores.

consideration. Also, for inspection purposes, the measuring of track geometry deviations (e.g. crosslevel, warp) are linked to the component group to which the cause of the deviation originates; primarily ballast and subgrade, but also rail and/or ties, as applicable (primarily gauge).

Knowledge-based as proposed for track inspection consists of using track priority score, condition indexes, condition index degradation rates and serious defect frequency to schedule detailed inspections for a given year. The inspection type options are proposed to consist of no detailed inspection, tie group only (including turnout ties), rail and fastenings group only, ballast and subgrade group only and various combinations thereof. By setting appropriate triggers (situation based on managerial policy) including a maximum time frame between inspections (e.g. 5 years), a detailed inspection plan can be prepared year by year. An example of this for a given set of information parameters follows below.

It should be noted that the authors are not suggesting at this time that safety inspection frequencies as required by regulation be modified. Compelling public safety considerations do not warrant a change to this long established and accepted practice.

The four criteria used in the knowledge-based inspection (KBI) methodology are divided into discrete ranges, shown in Tables 6–9. As a result, each track segment listed above falls into a TPS range, condition index range, degradation rate range and a number of serious defect occurrences per track mile. Note that in this paper when the generic "CI" is used, it represents the RJCI, TCI, BSCI or TSCI.

Table 10 lists the track segments in the example track network presented above (Figure 1), for which track priority scores have been derived, along with the current tie condition index calculated from the most recent detailed track inspection and the TCI degradation rate, derived from historical condition information. The serious defect occurrence rate over the past year is also displayed. For brevity, only the TCI is used in the example below, but in reality all of the indexes (RJCI, TCI, BSCI and TSCI) would also be used in concurrent analyses.

Table 6. TPS ranges.

Description	Inspection level	Lower	Upper	Range
Inactive	Inactive	0.00	0.00	0–0
Low	Low	0.00	0.25	0–0.25
Moderate	Moderate	0.25	0.50	0.25–0.5
Elevated	Elevated	0.50	0.75	0.5–0.75
High	High	0.75	0.90	0.75–0.9
Critical	Critical	0.90	1.00	0.9–1

Table 7. CI ranges.

Description	Inspection level	Lower	Upper	Range
Excellent	Low	86	100	86–100
Very good	Elevated	71	85	71–85
Good	High	56	70	56–70
Marginal	Critical	41	55	41–55
Poor	Moderate	26	40	26–40
Very poor	None	0	25	0–25

Table 8. Degradation rate ranges.

Description	Inspection level	Lower	Upper	Range
High degradation	High	5	N/A	>5 pts/year
Elevated degradation	Elevated	3	5	3–5 pts/year
Moderate degradation	Moderate	1	3	1–3 pts/year
Low degradation	Low	0	1	0–1 pts/year
No degradation	Limited	0	0	0 pts/year

Table 9. Serious defect occurrence ranges.

Description	Inspection level	Lower	Upper	Range (#/mile)
High occurrence	High	3	N/A	>3
Moderate occurrence	Moderate	1	3	1–3
Low occurrence	Low	0	1	0–1
No occurrence	Limited	0	0	0

Table 10. KBI criteria values.

Track segment	TPS	TCI	TCI degradation rate (pts/year)	Serious defect rate (#/mile)	TPS range	TCI range	Degradation rate range	Serious defect occurrence range
T11	0.953	75	4.50	0.91	Critical	Elevated	Elevated	Low
T12	0.885	95	0.94	2.78	High	Low	Low	Moderate
T13	0.524	61	4.44	1.00	Elevated	High	Elevated	Low
T14	0.740	100	0.00	0.00	Elevated	Low	Limited	Limited
T21	0.374	66	0.23	2.62	Moderate	High	Low	Moderate
T22	0.155	85	2.91	3.28	Low	Elevated	Moderate	High
T23	0.261	54	3.02	2.53	Moderate	Critical	Elevated	Moderate
T31	0.238	25	3.69	0.23	Low	None	Elevated	Low
T32	0.137	91	1.17	2.49	Low	Low	Moderate	Moderate
T33	0.164	73	2.40	2.86	Low	Elevated	Moderate	Moderate
T41	0.136	78	1.37	2.35	Low	Elevated	Moderate	Moderate
T51	0.090	31	3.05	1.14	Low	Moderate	Elevated	Moderate

For KBI scheduling considering the current condition, a CI/TPS matrix is developed to identify a desired track inspection frequency given the segment's CI and TPS (Table 11). For example, a high TPS and CI in the 56–70 range results in a recommended track inspection frequency of once per year. This is due to the mission importance of the track and the fact that its condition range is likely to benefit the most from a detailed track inspection. Alternatively, a low TPS with a CI in the 86–100 range results in a recommended frequency of every 5 years, which represents the maximum desired inspection interval. Also of note, segments with a TPS of 0 indicating inactive track, or CI below 25 indicating total rehab needed (e.g. out-of-face tie renewal) recommend no inspection ("N/A") since detailed track inspection is of minimal value for these segments.

Table 11. CI/TPS inspection interval matrix.

			TPS					
CI range	Description	Inspection level	Inactive	Low	Moderate	Elevated	High	Critical
86–100	Excellent	Low	N/A	5	5	5	4	3
71–85	Very good	Elevated	N/A	4	4	3	2	2
56–70	Good	High	N/A	3	3	2	1	1
41–55	Marginal	Critical	N/A	2	2	1	1	1
26–40	Poor	Moderate	N/A	4	3	2	2	2
0–40	Very poor	None	N/A	N/A	N/A	N/A	N/A	N/A

Likewise, for KBI scheduling considering the projected degradation rates, a CI degradation/TPS matrix is developed to identify a desired track inspection frequency given the segment's degradation rate in points per year and track priority score (Table 12). Here, segments with a high TPS and high rate of degradation would receive more frequent inspections, while lower importance segments with less degradation would receive less frequent inspections. Again, no inspection is recommended for inactive tracks where TPS equals 0.

To consider the serious defect occurrence from the last safety inspection, a Safety Occurrence/TPS matrix is developed to identify a desired track inspection frequency given the number of serious defects identified per track mile and track priority score (Table 13). Here, segments with a high TPS and rate of serious defect occurrence would receive more frequent inspections, while lower importance segments with less frequent occurrence would receive less frequent inspections. Again, no inspection is recommended for inactive tracks where TPS equals 0.

Using this methodology, a track segment component inspection frequency schedule can quickly be identified, especially with the use of spreadsheet software. The overall inspection frequency is the minimum of the three frequencies identified under the individual condition, degradation and serious defect rate considerations. The one

Table 12. CI degradation rate/TPS inspection interval matrix.

			TPS					
CI degradation rate	Description	Inspection level	Inactive	Low	Moderate	Elevated	High	Critical
>5 pts/year	High degradation	High	N/A	3	2	2	1	1
3–5 pts/year	Elevated degradation	Elevated	N/A	4	3	3	2	2
1–3 pts/year	Moderate degradation	Moderate	N/A	4	4	4	3	3
>0–1 pts/year	Low degradation	Low	N/A	5	5	4	4	3
0 pts/year	No degradation	None	N/A	5	5	5	4	3

Table 13. Serious defect occurrence/TPS inspection interval matrix.

Occurrence rate (#/mile)	Description	Inspection level	TPS					
			Inactive	Low	Moderate	Elevated	High	Critical
>3	High occurrence	High	N/A	2	2	1	1	1
1–3	Moderate occurrence	Moderate	N/A	3	3	2	2	2
>0–1	Low occurrence	Low	N/A	4	4	3	3	3
0	No occurrence	None	N/A	5	5	5	4	3

exception is if one of the frequencies returns a "N/A" value, no inspection is recommended. The recommended frequency represents the scheduling, in years, of the next detailed inspection from the last one. The next set of inspection data will cause the condition indexes and the degradation rates to be recomputed and the frequency revised, if needed. Continuing with the example for the sample network (Figure 1), Table 14 shows the recommended detailed inspection frequency for the tie component group. In practice, recommendations would be made for all of the component groups and a consolidated inspection plan would result.

Finally, when performing a detailed inspection of one or more component groups within a track segment, the inspector should be observant to any serious defects residing in the other component groups. In essence, while conducting a detailed inspection for some of the track components, a safety inspection will be performed on the remaining components. Consideration should be made to conduct the planned detailed inspection in conjunction with a regularly scheduled safety inspection. This would avoid an extra inspection trip. The overall detailed inspection plan covering different component groups in the various track segments could be coincided with multiple safety inspections inasmuch as the safety inspection frequency is greater than the detailed inspection frequency. This could help balance the effort required for inspection over the course of a year.

Table 14. Recommended tie inspection frequency (years from last inspection).

Track segment	Tie condition index criterion	Degradation rate criterion	Serious defect occurrence criterion	Overall recommendation
T11	2	2	3	2
T12	4	4	2	2
T13	2	3	3	2
T14	5	5	5	5
T21	3	5	3	3
T22	4	4	2	2
T23	2	3	3	2
T31	N/A	4	4	N/A
T32	5	4	3	3
T33	4	4	3	3
T41	4	4	3	3
T51	4	4	3	3

4. Future research considerations

While the methodology proposed above is used for scheduling and optimising a "knowledge-based" track inspection plan, the authors have identified its applicability for M&R planning as well. Of particular interest is the selection of M&R activities under a constrained budget, which is the typical operating environment for most railroads, including military, shortline and industrial railroads. There are different approaches currently available for prioritising track M&R work activities, but the authors surmise that a "mission-focused" methodology is a cornerstone to "knowledge-based" optimised M&R planning. Such planning could be accomplished through a multi-criteria prioritisation approach which includes the mission-focused track priority scoring methodology. Since each candidate work action belongs to a track segment and has an associated cost, the budgeting process will quickly identify the highest priority activities to perform in each year based on budgetary constraints. Methods are being researched by the authors to determine how the track priority scores calculated above, condition metrics, track standards compliance requirements, local and global work actions and M&R policies can be used and combined to develop an optimised M&R strategy under a constrained budget.

Also, the authors have not addressed the concept of applying a "knowledge-based" approach to optimise the scheduling of safety inspections. Using the same principles described in this paper and the addition of a risk assessment should form the basis for such an approach. Research is needed to expand and refine the KBI for this safety-driven application.

5. Conclusions

A knowledge-based approach to inspection developed for building components and endorsed by the NRC can be expanded to include other facilities such as railroad track. By incorporating a track priority score and condition metrics, detailed inspections no longer need to be scheduled by the calendar, but rather by mission and asset management needs. For those railroads with maintenance standards, standards will likely need to be revised to incorporate a KBI approach. Those railroads without an applicable maintenance standard or who do not incorporate detailed maintenance inspections in their business practice should consider initiating a mission-focused KBI approach as a means for improving their overall track asset management. Either way, a mission-focused KBI approach will optimise the allocation of inspector resources and pay dividends on improved M&R planning as well. The KBI approach presented in this paper and the condition metrics used are focused on the small railroad (military, shortline and industrial) niche that is also the application for the RAILER® SMS asset management tool that will automatically compute those indexes from detailed inspections. However, a KBI approach has wide implications and can be applied to Class I and other railroads as well, using the applicable set of condition metrics. Likewise, the track priority score methodology introduced in this paper has broad implications.

The trigger values used in the example need not be fixed. Rather, the authors intend for them to be flexible and responsive to managerial needs. To illustrate this point, the example imposed a 5-year maximum interval between detailed inspections. The location, operation and overall management philosophy of a given railroad may warrant a different maximum.

A KBI approach for scheduling safety inspections is not recommended at this time. There are two primary factors for making this recommendation. First, public safety considerations are compelling and, as such, research is needed into incorporating risk directly into the overall KBI process. Second, any change to the requirements of the FRA Safety Standards would require a lengthy process and change to the federal regulations.

Finally, a mission-focused, knowledge-based approach to M&R planning is proposed as a viable alternative to the commonly used compliance-based approach. Research is underway to transform the concept into a practical application.

Declaration of interest

The authors do not purport to reflect the views of the US Army, US Department of Defense, or the University of Illinois Railroad Transportation and Engineering Center.

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