A critical review of Information Assurance (IA) framework for condition-based maintenance of railway tracks

Y.K. Al-Douri & P. Tretten

Division of Operation and Maintenance Engineering, Lulea University of Technology, Lulea, Sweden

ABSTRACT: Railway maintenance is faced with increasing demands, including the need to improve service. Data measuring the track state and suitable models or applications are needed to make good maintenance decisions. This critical review paper investigates many research papers on the use of information assurance (IA) within condition-based maintenance (CBM) on a railway track. An IA framework sheds light on the data and information used to make maintenance decisions. The paper considers work on data processing and decision-making in CBM. The results show condition monitoring suffers from an inability to determine exact positioning on the track; some data are inaccurate or unavailable. Existing studies have not adequately dealt with data content or the various technologies used. They focus on integrity, availability, authentication, authorisation and accuracy, but do not consider other IA principles important to understand data. CBM models and algorithms have difficulty understanding degradation models, and data problems mean it is difficult to make good decisions. There is a lack of long term maintenance plans. Models also need to be integrated for more realistic but not necessarily optimum solutions and to ensure practical predictions of maintenance. Some models focus on degradation, others consider prediction, and still others calculate the maintenance cost; it is difficult to combine these. Overall, data are inaccurate, there is no testing phase using realistic data, and existing models are insufficient. This has a negative impact on maintenance decisions.

1 INTRODUCTION

Railway transportation traffic has increased, affecting the track condition. To ensure good service, maintenance needs to be well planned and correctly conducted – and this can be difficult. A condition-based maintenance strategy (CBM) can monitor the track state to facilitate maintenance decisions. An open system architecture for condition-based maintenance (OSA-CBM) follows a specific sequence of steps: collecting track data, evaluating the data on the track state to determine their behaviour and make decisions on maintenance, and, finally, carrying out maintenance. A recent study shows both measurement and analysis problems, as data can be incomplete and/or inaccurate (Al-Douri, Tretten et al. 2016).

Several frameworks can enhance communication between OSA-CBM layers to make better maintenance decisions. These frameworks focus on improving the decision making from a business perspective and decreasing the cost of doing maintenance. However, there is a need for a framework able to consider technical and business drivers together. Information assurance (IA) offers a framework able to deal with each strategy level and from two main perspectives: information/data and systems and application based on the main drivers (i.e., technical and business). The IA framework can help an organisation understand data behaviour and information processing. This, in turn, will lead to better railway track decision making.

This critical review paper investigates research papers on the use of an information assurance (IA) framework for condition-based maintenance (CBM) of a railway track. The goal is study the research gaps in the condition monitoring data, models, and algorithms used to make maintenance decisions. Many papers, including theory, practical applications and reviews, have appeared in academic journals, conference proceedings, white papers and technical reports.

The collected papers are categorised based on the various steps of the OSA-CBM layers, particularly focusing on data processing and maintenance decisions; they are then set within the IA framework’s levels of data/information and systems and applications. To identify the patterns and trends in the literature, the paper formulates the following research question:

• In what way(s) does the information assurance framework implemented in condition-based maintenance (CBM) improve maintenance decision making?

To answer the research question, it begins with research papers related to the IA information/data layer. It goes on to study models and algorithms related to systems and applications.
2 THEORETICAL OVERVIEW

A railway track provides a stable and safe platform for a train (Tzanakakis 2013). The deterioration of the track negatively affects overall performance and may even stop service. Good maintenance can increase safety and minimise cost (Andersson, Murray et al. 2004), but it is essential to monitor and assess the track (Kumar, Nissen et al. 2010).

2.1 Condition-based maintenance

Condition-based maintenance (CBM) is one of the main maintenance strategies; in this strategy, maintenance actions are determined by monitoring the condition of the track. When the track deteriorates to the point at which deterioration can be detected, it can be corrected and failure can be prevented (Jardine, Lin et al. 2006). Steps in CBM include inspection, the evaluation of the results and the determination of the proper maintenance actions (Kumar, Espling et al. 2008). That said, it may be difficult to use CBM on a complex infrastructure like a railway track, especially as a short-term maintenance strategy is required to control track irregularities (Al-Douri, Tretten et al. 2016).

Implementation of CBM may include integrating hardware and software components, for example, in an open system architecture for condition-based maintenance (OSA-CBM) (Holmberg, Adgar et al. 2010). OSA-CBM is designed to ensure nonproprietary and flexible communication between the CBM functional blocks. First, data are gathered by sensors and digitalised. Then, data are manipulated and the relevant features are extracted to determine the current state of the track. Threshold boundaries are used to assess the track health, i.e., whether the track is close to a boundary in any particular area. Prognostic assessment forecasts the future state, i.e., when the track will pass a threshold. Finally, decision support integrates the various data to allow maintenance decisions. Figure 1 shows these functional blocks (SS-ISO 13374-2 2007).

The OSA-CBM layers are supported by different external systems and data resources. Figure 1 shows the three main steps: data collecting, data processing and maintenance decision making. In data collecting, the track is measured and measurements are digitalised; this step is not included in this review study. Data processing considers the collected data with respect to the relevant parameters and setup limits. Decision making uses models and algorithms for diagnosis and prognosis of track irregularities. A framework is required to ensure proper data and good information are available for maintenance decisions.

2.2 Information assurance framework

Information assurance (IA) refers to a collection of methodologies and services that are crucial to maintain the integrity of operation with respect to the people, information and infrastructure (Willett 2008). IA works to maintain operation, despite unusual events that might corrupt it (Andrew and Kovacich 2006).

An information assurance framework can apply to the behaviour of a structure, of a system, or of data. It considers technical risks and provides solutions (Hamilton Jr 2006; Willett 2008). The framework has six architectural views (figure 2) (Willett 2008): people, policy, business, process, systems and applications, information/data and infrastructure. This review focuses on information/data and systems and applications to study data behaviour and information processing.

Four architectural components of the IA framework (figure 2), i.e., organisation, infrastructure, information/data and systems and applications, are partially compatible with three OSA-CBM steps, i.e.,
data collecting, data processing and decision making with models for diagnostics and prognostics. The framework protects and defends information, systems, and applications (Korotka, Roger Yin et al. 2005). IA principles are confidentiality, integrity, availability, possession, utility, authenticity, non-repudiation, authorised use and privacy (Willett 2008; Qian, Tipper et al. 2010).

The framework can be applied using Enterprise Life Cycle Management (ELCM). As shown in figure 2, the ELCM process begins with an idea or concept, in this case, IA. The architect shapes the concept, and the engineer adds a technical perspective. In the acquire/develop step, the concept is enhanced by a focus on the core principles mentioned above. Implement is clear: in this step, the concept is applied in the organisation. Its efficacy must obviously be tested before full deployment in a single location or many locations. Personnel must be trained in its use for full deployment to be effective. IA is then run throughout the operation and maintenance of the assets in question until they are retired at the end of their life cycle, and the process is complete. (Willett 2008).

3 CBM INFORMATION/DATA

In this paper, information/data refers to the condition monitoring (CM) data on the railway track. CM data are collected to measure the track vertically and horizontally and determine the track status. Numerous issues arise during the processing of measured data, as shown in Al-Douri, Tretten et al. (2016), hence the need for IA.

Information assurance principles are applied to each architectural view to understand data behaviour and to shed light on how information is processed for maintenance decisions. Generally speaking, a quality assurance system proposes to improve the overall data quality (Houston, Hiederer 2009). It represents a systematic way to assess the adherence of the process to the principles and then to eliminate errors and uncertainty before data are ready to use. It turns poor data into good data; at the same time, it avoids problems that can arise when several data sources are integrated. Common data problems include missing data, inconsistent data, incorrect data, and unusable data (i.e., not understandable).

Another study looks at authorisation and authenticity in communication and message transfer within the system life cycle (Monfelt 2011). It considers the relationship of reliability, maintainability and maintenance with confidentiality. The study implements an information security management system (ISMS) to evaluate the effectiveness of presuppositions, strategies, tactics, operations and concluding audits. This will assure system-wide communication.

However, in the railway industry, a large quantity of data is collected from sensors monitoring the railway track. These large data need to be reduced to useful information. A UK study proposes using in-service vehicles and Unattended Geometry Measuring Systems (UGMS) to determine the accuracy of data, including track location (Weston, Roberts et al. 2015). Data need to indicate the current state of the track geometry, but sensors have problems collecting the data required to feed the decision-making process. The data in this study of the UK railway show a lack of accuracy. With the integration of other positioning resources, there will be more data, leading to more accurate degradation models and better maintenance decisions.

A positioning system using satellites is helpful in determining track position and reduces the cost of installing and maintaining trackside equipment. A nonlinear combinatorial data reduction model has been proposed for a large amount of positioning data. The model can decrease the memory space and speed up train positioning; it has three algorithms based on the following three concepts: Looking Ahead, Dichotomy, and Breadth-First strategy (Chen, Fu et al. 2010). It finds data reduction is a large scale combinatorial problem, with bigger error bounds, for example; the selected algorithm must be close to optimal in performance to improve efficiency.

Another study expands the coverage of the integrity monitoring of the track to include the track map database, where map-matching estimates the error bound using a match residual and applying a global approach called Horizontal Protection Level (HPL) to achieve local solutions (Liu, Cai et al. 2014). This approach is used to determine the track position and constrain the filtering errors. It improves the availability of integrity monitoring and controls operation with respect to database accuracy and integrity.

A Global Navigation Satellite System (GNSS) and a railway track data system can take uncertainty into account. Unfortunately, the accuracy of the railway network database is uncertain, affecting the ability of GNSS to determine train location and ensure safety. The spatial railway track data must be integrated with GPS to assess the train location using mathematical models (Zheng, Cross 2012). The integration should increase the database accuracy with respect to positioning, improve availability and decrease cost in order to meet the new Required Navigation Performance (RNP) standard. The proposed integration requires more complete data but avoids the weakness of GNSS by integrating other sensors or by investigating other methods.

Table 2 shows the selected papers, along with the main advantages and disadvantages of their proposed systems.

4 SYSTEMS AND APPLICATIONS OF CBM FOR DECISION MAKING

Systems and applications refer to the models and algorithms used in CBM for understanding and predicting railway track irregularities for maintenance decisions. Sufficient and efficient assessment of railway track irregularities is crucial for maintenance decisions. However, limitations in the existing models and
An approach using a Markov stochastic process can deal with track geometry data (Askarinejad, 2010). It is relevant to applications where few parameters are required to understand deterioration. Moreover, greater selectivity of parameters is required to adapt to the complex infrastructure of a track. A statistical and engineering approach suggests a way to deal with comprehensive track field data for 100 km of railway line over a period of two years. The model calculates the railway track degradation using the gathered data (Sadeghi, 2011). It deals with track geometry data and track structure data to understand track irregularities, but more mathematical development is required to estimate the future condition of the track.

Track irregularities have an effect on train safety. An approach using a Markov stochastic process can evaluate deterioration using maintenance units. In the proposed process, a hazard model uses heterogeneous maintenance units and a Markov transition matrix (Bai, Liu et al., 2015). A heterogeneous maintenance unit is found to play a significant role in deterioration rates, but deterioration is faster when other factors come into play. Moreover, greater selectivity of parameters is required to understand deterioration.

Multi-objective optimisation of geometrical and mechanical properties of the railway track requires a moving load representative train axel for a high speed railway track. A genetic algorithm has been proposed to optimise an effective quasi-optimal solution with low search effort (Rodrigues, Dimitrovoá, 2015). The model shows how the behaviour of the railway track is influenced by various parameters required to optimise the railway track and its components. Genetic algorithms require low search effort and are sufficiently robust and versatile for different types of analysis. Unfortunately, the model does not consider all parameters; for example, more study of optimum ballast height is required.

A new method called Fuzzy Track Monitoring System (FTMS) has been proposed to estimate track irregularities on the running time (Chellaswamy, Akila, 2013). It estimates the lateral and vertical irregularities using a fuzzy controller with the ability to deal with real time measurements. The data sources are sensors, controller, GSM modern and GPS tracking system. The method has limitations understanding positioning on the track during system vibration.

Artificial neural networks (ANNs) have been adapted to study Turkish railway track geometry deterioration over a period of two years on approximately 180 km of track (Guler, 2014). The model develops the significant relationships between the main track geometry parameters. The ANN architecture consists of 12 input neurons, 14 neurons in hidden layers, and 1 output to understand the relationship between the parameters and track deterioration. This model is suitable under certain conditions, but it is complex. In addition, numerous other factors such as dynamic train loads, substructure, material properties and environmental conditions have an effect on deterioration.

### Systems and applications of track irregularities

The Bayesian approach proposes a degradation model with heterogeneous degradation rates using the Wiener process to determine errors in data measuring. This model studies the unit degradation and accounts for the heterogeneity and statistical uncertainty of condition monitoring with imperfect inspections, because all models are estimated using data with statistical uncertainties or data from experts (Ye, Chen et al., 2015). The model may help to determine more robust condition monitoring techniques.

A Bayesian methodology may be able to investigate a suitable form of the prior distribution and study how the uncertainty parameters affect prior distribution and expert option. Bayesian methodology for scheduling uses Monte Carol simulation (Percy, 2002). This approach is relevant to applications where few data are available and it is considered to have accurate results. However, the proposed methodology needs to be implemented to study its potential benefits.

Techniques for modelling railway track irregularities need to be improved to adapt to the complex infrastructure of a track. A statistical and engineering approach suggests a way to deal with comprehensive track field data for 100 km of railway line over a period of two years. The model calculates the railway track degradation using the gathered data (Sadeghi, Askarinejad, 2010). It deals with track geometry data and track structure data to understand track irregularities, but more mathematical development is required to estimate the future condition of the track.

Track irregularities have an effect on train safety. An approach using a Markov stochastic process can evaluate deterioration using maintenance units. In the proposed process, a hazard model uses heterogeneous maintenance units and a Markov transition matrix (Bai, Liu et al., 2015). A heterogeneous maintenance unit is found to play a significant role in deterioration rates, but deterioration is faster when other factors come into play. Moreover, greater selectivity of parameters is required to understand deterioration.

### Systems and applications to predict track irregularities

Maintenance needs to be improved, and stochastic reliability models are now including unknown parameters to improve maintenance decisions. In order to assess maintenance decisions and minimise maintenance,
a timeframe mathematical model (stochastically and continuously) suggests CBM inspection and replacement policies should consider unit deterioration (Grall, Bérenguer et al. 2002). To decrease the maintenance cost, the model studies unit deterioration using numerical experiments of random deterioration and perfect inspections. It uses the replacement threshold and the inspection schedule as decision variables in setting maintenance strategy. Unfortunately, it is difficult to identify real maintenance cases using this method; it is also difficult to achieve perfect inspections for physical structures.

A novel technique develops the use of a non-linear regression equation. This equation is updated based on track irregularities and the track waveform history data (Xu, Sun et al. 2011). The model can predict a 200 m track unit section every day over a short time range. Certain types of maintenance, such as tamping, have a significant influence on this prediction model, and it remains a short term prediction.

Other researchers consider errors in prediction and decision-making methods by examining the accuracy and robustness of these techniques. Statistical Process Control, Hidden Markov Model, and Proportional Hazard Model have been simulated using the Monte Carlo method (Orth, Yacout et al. 2012). Each technique uses two main types of error: the first is performing preventive maintenance while the system is in a normal state; the second is deciding the system in a normal condition when it is not. Accuracy and robustness should be considered when the maintenance decision is made, as data inputs and the value of these inputs significantly affect the quality of the decision. Data are randomly generated and are not related to real systems, but even so, these models can be relevant to specific problems.

The Multiple-Criteria Decision-making methodology has been proposed to select an optimal mix of maintenance approaches (Ghosh, Roy 2009). The framework evaluates Corrective Maintenance (CM), Time-Based Preventive Maintenance (T BPM) and Condition-Based Predictive Maintenance (CBPM) for different equipment conditions. The evaluation uses a three-tier Analytic Hierarchy Process (AHP), a combination of risk ranking, fuzzy AHP and Genetic Programming (GP). The method provides a sufficient maintenance management process through generalised decision-making. The theoretical framework is complex, but it combines the advantages of three techniques, provides for improvement, optimises multiple objectives such as risk reduction and cost minimisation, and generalises decision-making.

One study implements multi-state linear prediction to predict track irregularities accurately and eliminate hidden danger. The method shows the regularity in the changes in peak values over time by using linear relationships and speed types (Guo, Han 2013). The model enhances prediction and decreases danger, but has accurate results only in short term predictions.

Another study predicating track performance develops a good mathematical model with the best data set. In the study, linear and nonlinear models are used to fit the data and the performance using Monte Carlo simulation (Liu, Schutz 1998). The study compares previously reported mathematical models on their assumptions, weaknesses and predicted perspectives, and then develops a test for a new model. The results of the new exponential model are related to time and historical years. It has the best performance for predicting world records and ultimate performance; a random sampling model to predict the future is within distance.

Artificial intelligence improves CBM decision making. One study suggests methodologies for solving problems by adapting the solutions to historical problems. Many methodologies, such as rule-based reasoning, fuzzy, neural networks, and genetic algorithms, can find a solution based on the problem statement (Watson 1999).

In one proposed model, the genetic algorithm (GA) determines the optimal degradation level as a frame for a multi-objective search. The model evaluates Monte Carlo (MC) simulation (Marseguerra, Zio et al. 2002). The GA uses the Euclidean distance to search for the degradation threshold of MC that will optimise maintenance. The model achieves the optimal threshold of degradation using data on system availability, but a challenge is choosing a threshold among a large number of alternatives. A huge random population is generated over the process as well.

A genetic algorithm and genetic programming methodology proposes a way to plan track maintenance; the method shows good results over a short track section. The function set contains both arithmetical and logical calculations for the relevant parameters with a random population (Grimes 1995). This model is not efficient over long distances or a big search space.

A group of researchers proposes using multilayer feedforward neural networks based on multi-valued neurons (MLMVN) to formulate a time series for reliability and degradation prediction problems on railway track turnouts (Fink, Zio et al. 2014). This model predicts reliability without showing accumulative errors. It can improve prediction and increase flexibility by integrating additional influencing parameters. More work is required for long-term predictions, as time series data are not sufficiently long. More work is also needed on the generating process and precise decision making.

A fuzzy approach uses Simulated Annealing (SA) to study train delays (Shafia, Sadjadi et al. 2012). The model presents a better solution for robust periodic train scheduling while considering noise in travelling times. It also works on optimising timetables for a single track train but focuses on shifts and delay times in the timetables for all trains and the relevant illustrated data.

Optimising Life Cycle Cost (LCC) is a main goal to achieve track availability. Decision Support System (DSS) proposes efficient condition maintenance by overcoming the drawbacks of other models. Fuzzy
logic using the Gaussian membership function is able to handle thresholds through artificial neural networks (ANN) to obtain the track deterioration (Ottomanelli, Dell’orco et al. 2005). The model can analyse data for track section and then plan maintenance and optimise available resources by using the fuzzy function for input and output data in ANN. Unfortunately, data are simulated, representing a major drawback of this model.

Table 3 shows some selected papers with their main advantages and disadvantages.

5 DISCUSSION

Information/data and systems and applications layers in the information assurance (IA) framework are the link between the people and the organisation. These layers process condition monitoring data and disseminate information on the infrastructure. They are related to the CBM steps of data processing and decision making. The framework provides a guideline for understanding data behaviour and systems and for deriving and applying better maintenance decisions.

Together, information and data are the core of the CBM process. Data are collected on vertical and horizontal track measurements. The literature shows problems with data, such as positioning on the railway track. Data also suffer from a lack of accuracy because of difficulties with the infrastructure and technological issues. The existing studies do not focus on the other IA principles to assure data. Most of the literature assumes good data; this is neither efficient nor realistic.

Systems and applications can study track irregularities or predict performance in maintenance scheduling over time. But most degradation models only consider short periods or have limited input parameters, making it difficult to understand the track state. Some models suggest finding an optimum solution might be difficult for real track irregularities. Additionally, artificial intelligence models are required to study the actual state of the track. Finally, cost should be included in models calculating track irregularities but an individual model for calculating certain life cycle cost data is required.

6 CONCLUSION

This critical review paper investigates research papers examining how an information assurance (IA) framework, specifically its information/data and systems and applications layers, can be integrated with two CBM steps, data processing and decision making, for the maintenance of a railway track. It considers condition monitoring data for the track, CBM models, and algorithms (diagnosis and prognosis). The results show condition monitoring data have inaccurate and incomplete measurements for some track sections. The analysis of models and algorithms for diagnosis and prognosis shows that a good degradation model cannot always be created, resulting in difficulties making maintenance decisions. An IA framework can guide the CBM process from collecting data to the final decision making. Because there are proper data related to the actual state of the track and the processing of information is better, the maintenance decisions will improve and the risks and costs will decrease.

REFERENCES


