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INFRALERT: Linear Infrastructure Efficiency Improvement by Automated Learning and Optimised Predictive Maintenance Techniques

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Deliverable D3.2

Application of physical, data-driven and symbolic models from component to system level

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Task	T3.2. Integration of physical models in asset condition for component level T3.3. Symbolic and data-driven methods for nowcasting and forecasting		
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Executive Summary

This deliverable presents the methodology necessary for implementing linear asset condition nowcasting and forecasting models. For the assessment of the condition of a linear asset, different types of inputs and limits are required. This involves the geometric dimensions, material properties, operational or usage profile, external and human factors as well. The output variables or features are asset identification, asset historical maintenance interventions and asset condition assessment and prediction (WP3). These features are the input for Alert Management (WP4), RAMS analysis (WP5) and decision support for maintenance planning (WP6).

In order to predict the future behavior of linear assets, there are three types of modeling techniques, mainly; physics based, data driven and symbolic modeling. For physical modeling, it is important to investigate the physical mechanisms that have significant influence on the degradation process and failure events of linear infrastructure. This also includes the geometric dimensions and material properties of the asset, the operational or usage profile, external factors, and human factors. For railway and road deterioration, there are several physics-based models that have been proposed in the literature. A physics-based approach is based on the identification of potential failure mechanism for an asset. Hence, the main function and failure mode of major components of railway and road are identified and collected in this report. The models can be divided into 'microscopic' and 'macroscopic'. Microscopic models deal with the stresses on specific components, e.g. rolling contact fatigue and wear. These models, based on physical laws, empirical evidence or engineering judgments are mainly applicable for design purposes. Macroscopic models (system or multi-segment level) are used for network analysis and maintenance planning, e.g. on the basis of road and railway track geometry deterioration models. The data-driven models are, considered as black box modeling, predicts the future behavior by analysing the data obtained from the linear assets. There are several models provided in this report and also comparison is also studied for the best suitable scenario. The symbolic modeling depends on maintenance work orders, external factors and other factors of interest. In this report, a fuzzy based symbolic model is proposed to predict the behavior. The nowcasting and forecasting of the assets can be obtained from either of the above mentioned models.

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1 Introduction

Physical assets can be generally separated into linear and non-linear. Linear assets are the assets that spread from one spatial point to another and probably differ in design characteristics over the distance. An important consideration in maintenance modelling of such asset is dynamic segmentation, which allows multiple sets of attributes to be accompanied with any segment of a linear feature. Each time an attribute value changes it can "dynamically" locate the segment. Typical examples of the linear assets are railways, roads, pipelines and cables. Non-linear assets are confined to a size and specific location such as equipment, machine, fleet, etc., but in contrast to linear assets are not specific to a single location. Many linear asset networks consist of several non-linear assets, e.g. one railway track can connect to other railway track and many non-linear assets like railway stations, traffic control systems, power generating equipment and more importantly other parallel linear asset like power cables, etc. Deliverable D3.1 contains a more thorough description of the concept and terminology of a linear asset.

It is useful to provide a framework for model categorization models for linear asset health monitoring from component to system level. Per Ferreira and Murray (1997), the hierarchical form of the main categories of models can be divided into 'microscopic' and 'macroscopic' as depicted in Figure 1. The authors describe the categories from a railway perspective, however the description holds for any linear asset. Microscopic models deal with the stresses on specific components. These models, based on physical laws and engineering judgements or empirical evidence, are mainly applicable for design purposes. At the other end of the scale are the macroscopic models that are relevant for maintenance planning and decision support on an infrastructure network level, which is the scope of INFRALERT.

Many models exist that can predict component (or segment) deterioration. These models are broadly classified as Physical models, data driven models and symbolic models. These models are described in Chapter 5. Each one of those has its own advantages and disadvantages and applicability can be chosen based on the requirements and application. For road and railway, most important ones are wear rolling contact fatigue and geometry models. Segment degradation is related to road and railway geometry deterioration used for forecasting and maintenance planning tools.

Chapter 2 of this report describes the overall function or services provided by linear asset and thereafter explains functional decomposition of a linear asset. The asset condition information (i.e. the input and output features of the condition assessment) are described in Chapter 3. The description of degradation mechanism is given in Chapter 4 and the corresponding models are described in Chapter 5. The following subsections of this chapter briefly introduce nowcasting and forecasting methods for asset management as required for condition assessment of linear assets and development of effective maintenance strategies.

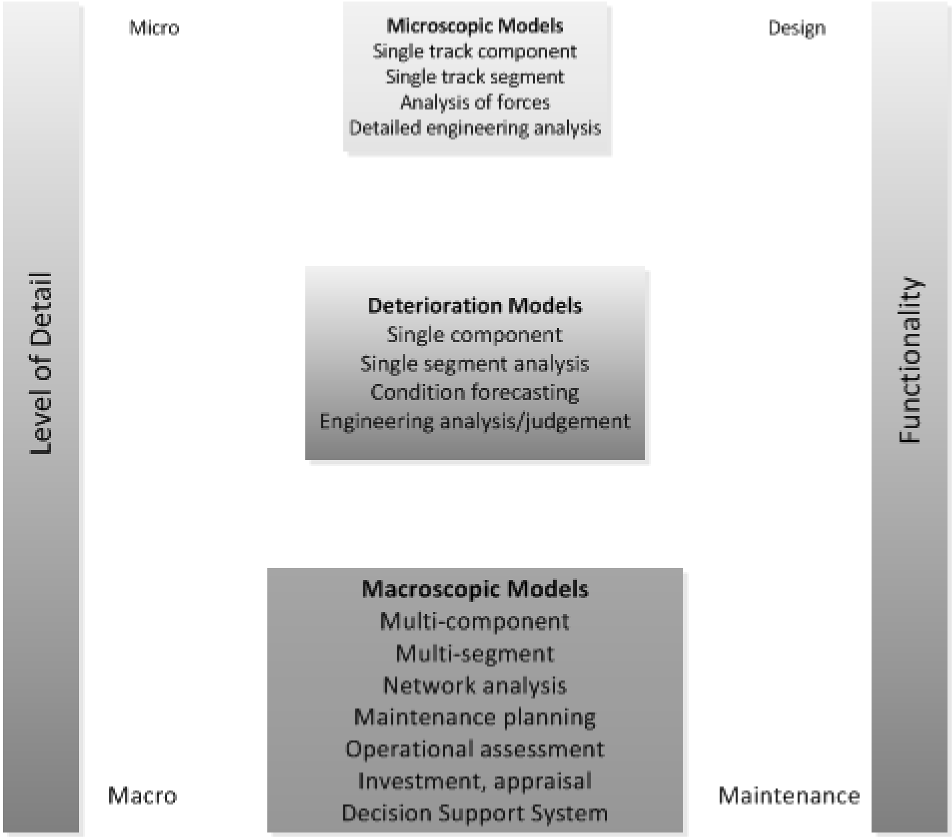

FIGURE 1: LINEAR ASSET MODELLING HIERARCHY (FERREIRA AND MURRAY, 1997)

1.1 NOWCASTING

Nowcasting is the basis of a robust decision-making process. According to the World Metrological Organization, nowcasting is the detailed description of the current weather along with forecasts obtained by extrapolation for a period of 0 to 6 hours ahead. Nowcasting is fact-based, focuses on the known and knowable, and therefore avoids forecasting. It is the basis of a robust decision-making process". A 'nowcaster' does not try to predict the future, but focuses what is known today, i.e., known now in real time. From railway operation or infrastructure management viewpoint, there are several inspection methods and systems that can be used for assessing the current condition of the assets.

1.2 FORECASTING

Forecasting is the process of exploiting past and present data to make deductions about the future. Forecasting can be carried out by diagnosis and prognosis by using the hybrid modelling consists of data-driven, physical and symbolic representation of the asset.

A symbolic model uses empirical relationships described in words (and sometimes numbers as well) rather than in mathematical or statistical relationships. A data-driven model relies on relationships derived from training data gathered from the system. A data-driven approach considers a condition indicator signal to be a set of random variables from a stochastic process represented by probability distributions. A model based on the physics of failure allows prediction of system behavior using

either an analytical formulation of system processes based on known principles or an empirically derived relationship. A hybrid model combines some or all three model types (symbolic, data-driven, and physical); more complete information allows more accurate recognition of the fault state.

2 Functional description of linear asset

Linear asset and infrastructure are expected to provide some functions which in turn should support required service or create desired value for the owner or user. In asset engineering and management, the integrity of an asset is to be preserved so that it can provide the required function or service. For example, the main service to be provided in linear asset management is movement of people, animals, goods, materials and other substances from one geographical location to another. To provide this service, all the constituent's systems, subsystems, modules, assemblies and components should function per infrastructural configuration and functional requirements.

Mapping and modelling of linear asset condition requires good understanding of the service that is expected to be delivered though the asset. Figure 2 shows the linkage between infrastructure condition and service quality. The development and application of physical and data driven models are aimed towards the achievement of set service quality. Further, the infrastructure data is used for state detection or state awareness by generating indicators to be compared with expected baseline profile values or operational limits. State assessments are based on operational context and sensitive to the current operational state or operational environment (Deliverable 3.1).

The information from state detection can be further used for functional assessment to infer the health status of the asset. Processing and modelling at this stage utilizes expertise from human or automated agent to determine the current health of the equipment and to diagnose existing fault conditions. It estimates the current health grade, potential failures and generates recommendations by fusing the digitalized condition information, state characteristics and relevant operational/environmental context. The health of the asset can be assessed as perfect, degraded, minimal or failed based on the level of function it can deliver. Finally, the provided quality of service can be obtained by assessing the performance of the infrastructure based on planned service/mission and customer expectations.

The description of service provided by linear asset in relation to its condition and functional capability is given in the next section.

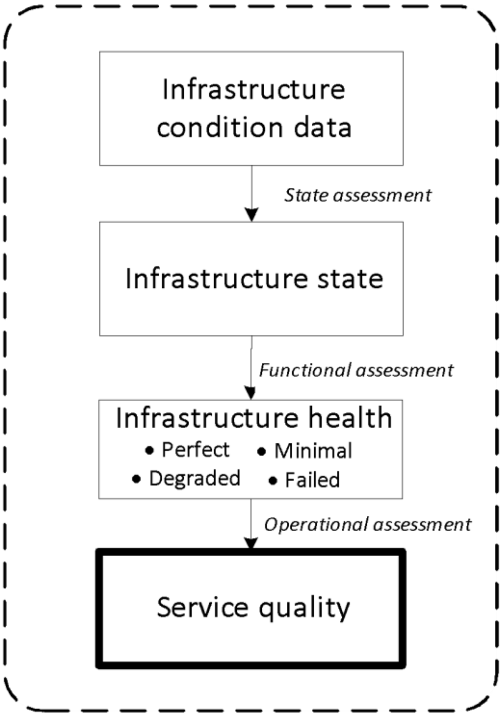

FIGURE 2: LINKAGE BETWEEN INFRASTRUCTURE CONDITION AND SERVICE QUALITY

2.1 PROVIDED SERVICE

The main value addition or service provided by linear infrastructure network can be described as the overall function required from it. As mentioned earlier this function is related to the expectations of the users and/or owner. The service provided is not a binary feature that can be zero or one depending on the state of the asset. Generally, railway and road infrastructure are degradable asset, thus the integrity of the provided service is a function of its state. A measure of the degree of conformance/satisfaction of infrastructure performance to standard expected by owner or user is called quality of delivered service (QoS). Even if all the items of a linear asset are in a state to perform their respective function, the quality of service is only guaranteed if none the items are in a degraded state. Functional degradation of a single critical item can result in delay or other impact on the quality of service. Some performance measures that are used in describing the QoS delivered on linear infrastructure are described below also in Table 1.

- Punctuality: The ability of transport to fulfil and deliver the planned travel and transport times and the ability to instantly provide correct and useful information during disturbed traffic. The definition of punctuality varies depending on the quality requirement of infrastructure owner or manager. It is common to use 5 minutes as acceptable deviation from the planned arrival time. That is, a train that arrives at its destination more than five minutes earlier or later than its scheduled arrival time is not punctual. Depending on the purpose of condition modelling, punctuality can be used as an output or target parameter.
- Robustness: The transport systems ability to prevent and handle incidents that causes disturbed traffic. In general, robustness is used to describe the ability of a system to maintain its ability to perform its function despite disturbances. These could be external or internal disturbances beyond the designed usage profile or conditions. It includes faults and

perturbations. Modelling the condition of asset for maintenance planning should support robust infrastructure and reduce uncertainties in the behavioral response due to disturbance. It should be noted that from maintenance viewpoint, robustness is a quality measure of service provided and infrastructure condition itself.

- Comfort: A measure of the QoS is the experience and perception of the travelling passengers of the track and ride quality perceived by travelling passengers. The ability of a transport system to limit the low frequency vibrations and accelerations which passengers are exposed to. This measure of service quality is a function of the condition of both fixed infrastructure and rolling stock. It is determined by vehicle design, track geometry and layout and the operational characteristics such as speed.

- Safety: The ability of transport systems to minimize the number of fatalities and seriously injured. In other words, it is the ability of an infrastructure network under certain circumstances and usage condition to be free from unacceptable risk of harm to people, asset, goods and environment.

- Usability: The transport systems ability to satisfy the different customer needs and requests for transport and travel.

- Capacity: This indicator is a quantitative measure of service provided by transport network, all the same, it is often linked to QoS and can be used as output parameter in condition modelling. It is the ability of transport systems to handle the requested volume of travel and transport. Infrastructure capacity is defined as the total number of possible paths in a defined time window, considering the actual path mix and quality demand from the market.

- Accessibility: The ability of transport system to make mobility possible for everyone with good quality and functionality throughout the country.

Maintenance department have the primary objective of assuring dependable and highly functional items and assemblies. From system of systems point of view, infrastructure maintenance should be related to the quality of service produced by a network. This informs the reason why most road and railway administrations has target for the service quality to be supported by maintenance process. These targets are based on road and track class, traffic, traffic volume and how passengers and train operating companies uses the system. Therefore, maintenance service providers adapt their strategic planning to meet the demand. The table below shows some of the delivery quality target for different road and railway classes, the condition of infrastructure asset is to be maintained so that the target could be achieved.

In addition, for road perspective, punctuality is not a direct result of the road system but it is achieved if each road stretch has the adequate capacity, assuring that each driver will reach the destination in the expected travel time. Considering the Portuguese case, the National Road Network Concession Contract which Infraestruturas de Portugal (IP) holds, sets its responsibilities based on the fulfilment of three types of performance indicators:

- Level of Service as defined on the Transportation Research Board Highway Capacity Manual (TRB, 2000), being related to each type of road hierarchy;

- Road safety (assuring a constant decrease rate of the severity and accident rates);

- Environmental sustainability (including several factors such as noise exposure across the road network).

TABLE 1: QOS TARGET FOR RENEWAL AND MAINTENANCE FUNCTION

	Basic	Level 1	Level 2
Punctuality	Road and railway should be available all through the year. There can be restriction for heavy traffic during certain period and significant deviation in travel time can occur	Road and railway shall be available all through the year. Minor deviation in the planned travelling time (arrival time) is acceptable	Road and railway shall be available all through the year. Deviation in the planned travelling time (arrival time) is expected to be insignificant
Robustness	Recovery potential and alternative detour should be possible	Recovery potential and alternative detour should be good enough	Recovery potential and alternative detour should be distinguished
Comfort	Trips should be realistic and comfort level should be satisfactory	Trips should be pleasant and comfort level should be good	Trips should be very pleasant and comfort should be additional value to delivered service
Safety	Trips should be possible with acceptable safety level and risk of harm	Trips should be possible with high safety level and low risk level of harm such that transport credibility is enhanced	Trips should be possible with highest safety level and insignificant risk level such that transport credibility is highly enhanced

2.2 FUNCTIONAL HIERARCHIES

Functional decomposition is a design method intending to reduce the complexity of the problem. Functional hierarchical of linear assets may have different levels and complexity. Hierarchies for railway and road are described below.

2.2.1 RAILWAY

The railway is comprised of complex systems which are interconnected, interrelated and integrated. A simplified hierarchical level of railway asset is shown in the Figure 3 (Deliverable D3.1). For the aims, different functional hierarchical levels of railway are identified. For instance, system of system, system, module, assembly and component are assumed as hierarchical level. Railway or road infrastructure in general consists of three types of assets; linear, non-linear and fleet. To assess the condition of the linear assets, it is essential to understand the condition of the non-linear assets and fleet, because there is frequent interaction among them. In this report, majorly, linear and non-linear assets are considered to understand its critical parameters.

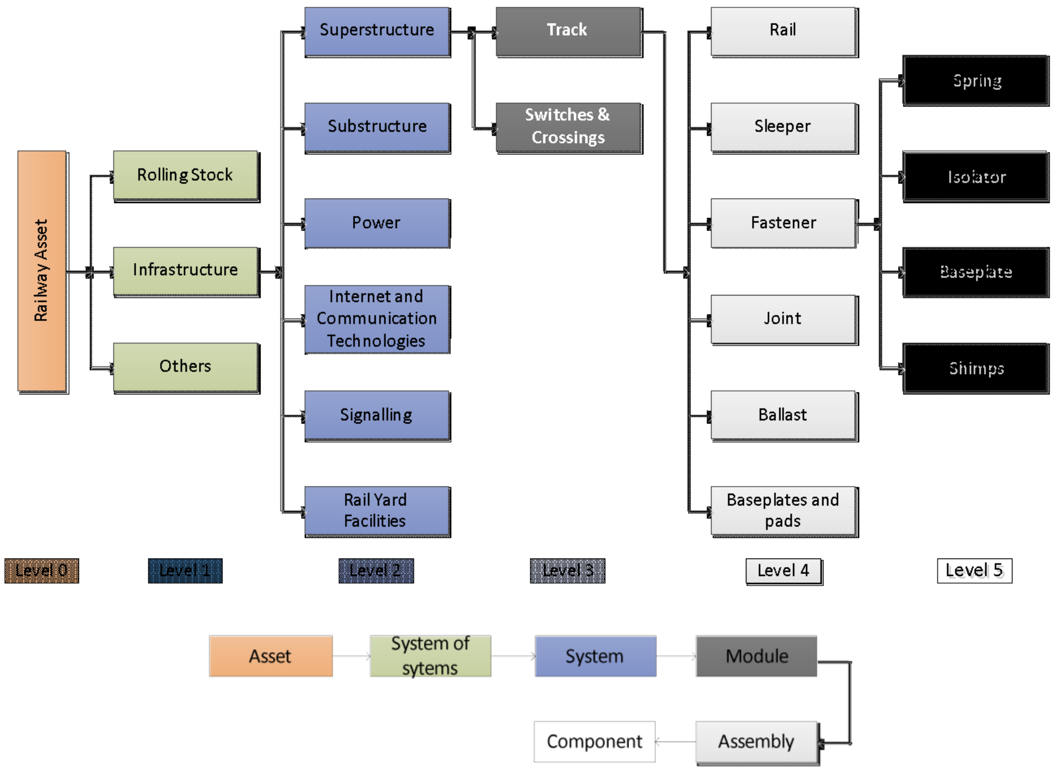

FIGURE 3: HIERARCHICAL REPRESENTATION OF RAILWAY ASSET

2.2.1.1 Superstructure

The different components of superstructure are shown in

Table 2.

M1. Track *(Linear Asset)*

- F1. Support movement of trains
- F2. Bear static and dynamic loads
- F3. Restrain the lateral, longitudinal and vertical track movement
- F4. Drainage
- F5. Retain geometry for ride comfort

M2. Switches & Crossings *(Non-Linear Asset)*

- F0. Allow vehicles to run over varying routes
- F1. Support movement of vehicles
- F2. Direct path of vehicles per signaling system commands

TABLE 2: COMPONENT FUNCTIONS

Assembly/Component	Function
M1.1 Rail	• Running surface • Guidance of train wheel • Stiffness - Transport wheel load to sleeper without deflection
M1.2. Sleeper	• Receive and distribute load over supporting ballast • Maintain gauge • Provide cant • Restrain the lateral, longitudinal and vertical rail movement by anchorage of the superstructure in the ballast
M1.3. Fastener	• Retain rail on sleeper
M1.4 Joint	• Insolation of rail • Provide possibility of expansion
M1.5 Ballast	• Distribute load • Absorbing shock from dynamic load • Anchor the track • Drainage
M1.6 Baseplates and pads	• Stiffness properties
M2 Switches and crossings	• Allow vehicles to run over varying routes • Support movement of vehicles • Direct path of vehicles per signaling system commands

2.2.1.2 Substructure

- Offers the final support to the track structure
- Bears and distributes the resultant load from the train vehicle through the track structure
- Facilitates drainage and provides a smooth platform, at an established grade, for the track structure to rest upon.

2.2.1.3 Power

The traction power supply system (TPSS) is one of the main systems in power category that provides adequate traction power for the electric railway vehicles. Power can be linear asset, non-linear asset or fleet, depends on the position of the power system. Different parts of an electric locomotive are shown in Figure 4. The TPSS is an essential system for the provision of a continuous and adequate electrical traction power for electric railway vehicles. Some of the main components are listed in

Table 3.

TABLE 3: POWER SUPPLY SYSTEM'S COMPONENTS AND ITS FUNCTIONS

Assembly/Component	Function
Power supply subsystem-substation	Where the voltage is step down an AC is converted to DC
Overhead line (Feeder conductors, contact conductors, suspension wire rope, conductor support structure, insulators…. -)	To convey the electric power from substation to locomotive
Traction subsystem	Electrical energy is converted into mechanical energy
Electric traction	Can be categorized as direct current traction or alternating current traction.
Rotary Frequency convertor	The motor convert electrical power to mechanical energy via shaft and the n convert back to electrical energy but in one phase at 16,7Hz, 25Hz,…
Static Frequency convertor	Converters supply single-phase traction power networks from three-phase networks. The structure can be based on cyclo-convertor, or PWM-thyristor-2level, PWM-GTO-2level, or PWM-GTO-3level.

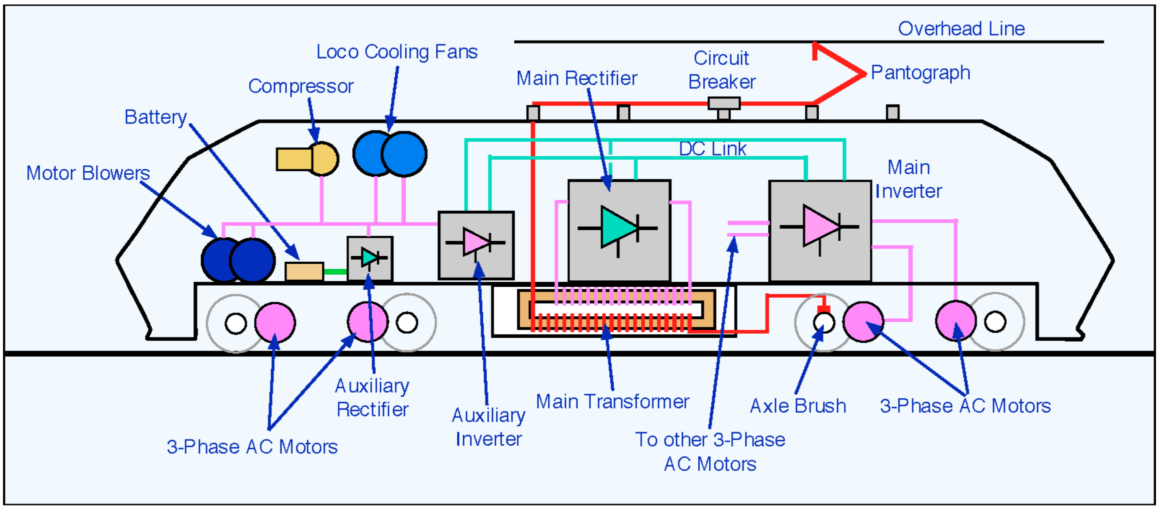

FIGURE 4: DIFFERENT COMPONENTS IN AN ELECTRIC LOCOMOTIVE (ELECTRIC LOCOMOTIVE GLOSSARY, 2016)

2.2.1.4 Information and Communication Technology (ICT)

Rail transport is becoming increasingly dependent on ICT (Narayanaswami and Mohan, 2013). Since, it is in the centralized location, it is a non-linear asset. The applications of ICT in Railway are listed below:

- Train operation
- Passenger Information, passenger ticketing, etc.
- Asset Management of track and rolling stock

- eMaintenance/Cloud-based Maintenance: The complexity of managing maintenance information, and the inflexibility and dwindling maintenance budget have led to the continuous deterioration of physical assets, and hence, there is a need to annex maintenance functions. eMaintenance is maintenance support by utilization of Information & Communication Technology (ICT). eMaintenance also supports different interconnected levels in an organization by provision of an effective and efficient infrastructure for decision-making (Abisuga et al. 2014).

The possible advantages of using ICT are increased operational flexibility and improved asset availability and utilization. ICT also enables the integration of different the infrastructure, operations, and rolling_stock providing a tool for real time decision making. In addition, ICT is the backbone of safety, alarm systems, video surveillance, and remote access monitoring. The role and application of ICT in railway industry are depicted in Figure 5.

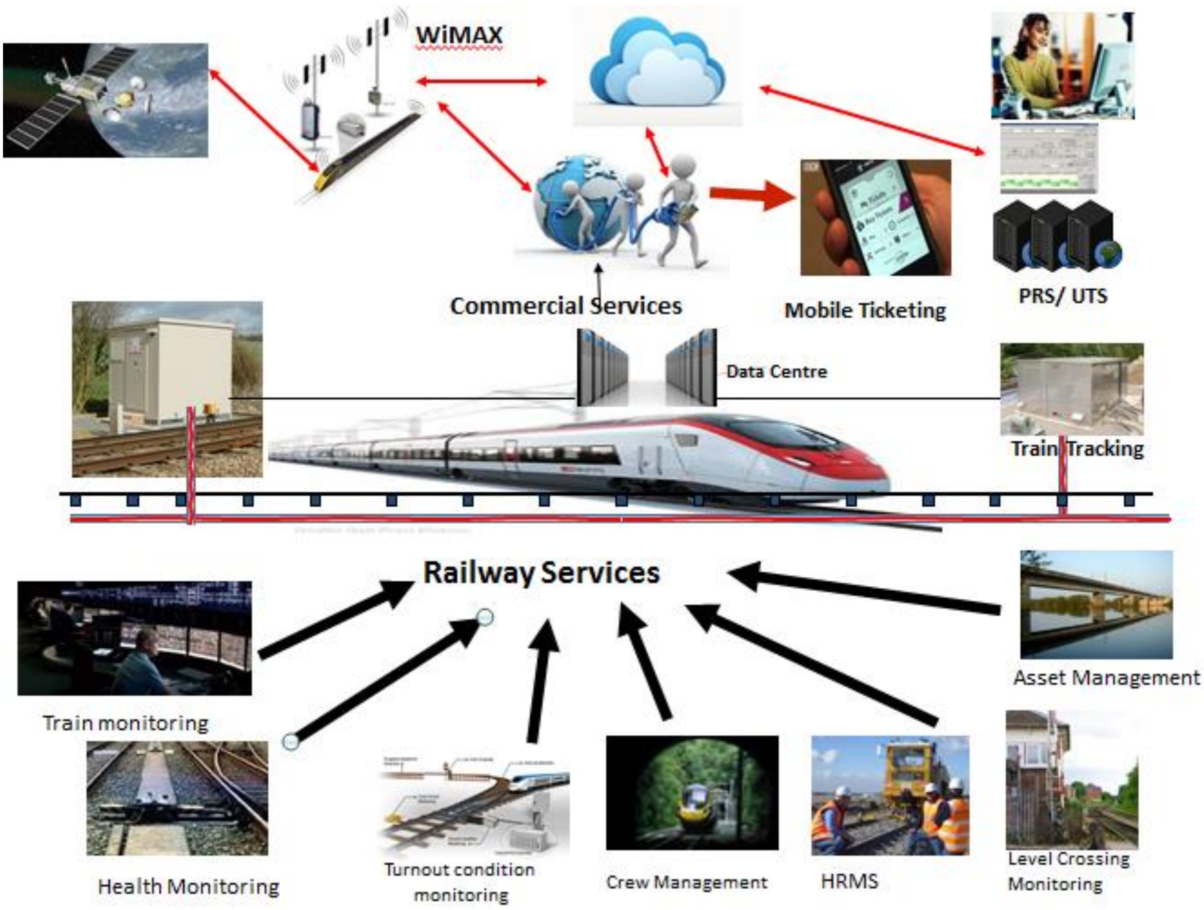

FIGURE 5: ICT APPLICATIONS IN RAILWAY INFRASTRUCTURE

2.2.1.5 Signaling

Railway signaling systems supervise, protect, and control the railway network to have safe transportation corridor. There are numerous items in the signaling systems to fulfil the aim. For example, track circuits, axle counters and GPS-based systems can be used to locate a train. Track circuits and signals can help to control the traffic on the railway line to prevent collisions. Depending

on the type of exchange of information between the infrastructure and the train, railway signaling systems can be classified into the following groups (Estevan, 2015):

- Infrastructure, wayside or lateral signaling *(Non-Linear Asset)*: This is limited to wayside signals informing the driver of operating restrictions. The driver is responsible for acting according those restrictions. This is only possible at low speeds, since it depends on the capability of the driver.
- Combination of infrastructure and on-board signaling *(Fleet)*: This type of signaling system can be considered intermittent or continuous. In intermittent transmission, the transfer occurs in a discontinuous way, e.g. transmission of information to train cabin through balises when the train passes above them. In continuous transmission, the information is exchanged continuously, via a radio system.

Subsystems of the Swedish signaling system are described in Table 4 (Trafikverket, 2012; Estevan, 2015).

TABLE 4: RAILWAY SIGNALING SYSTEM'S COMPONENTS AND ITS FUNCTIONS

Assembly/Component	Functions
Traffic management system (TMS)	Creates an interface between the traffic operator and the railway network.
Track circuits (TC)	Responsible for the train location
Balise group (BG)	Give input from the track to the on-board signalling system (e.g. speed limits, driving mode, etc.).
Level crossings (LC)	Coordinate the road traffic crossing the railroad.
Signalling boards (SB)	Give the train fixed information (e.g. on tunnels, bridges, speed restriction areas, etc.).
Signals	Give or restrict permission to the train on coming into a track section.
Interlockings (IXL) / Radio Block Centre (RBC)	Receive the input from the different systems (e.g. track circuits, level crossings, signals, TMS), and calculate and return as an output the train operation restrictions to ensure safe traffic operation.

2.2.1.6 Rail yard

Several types of equipment are required at a railway yards to ensure the safety of the railway system. The yards are usually equipped with end loading ramps, loading gauge, cranes, Weigh Bridge. This equipment is required for the convenience of passengers at stations and for handling goods in yards. Furthermore, buffer stop, scotch block, derailing switch, and sand hump to ensure the stoppage of the train. The yards are also equipped with other facilities, for instance platform lighting, Train and loco heating, locomotive sheds, ash pits, and turntables. These types of assets are considered as non-linear assets. The safety and efficiency of a station are greatly influenced by the quality of railway yard equipment (Chandra, 2008).

2.2.2 Road

The hierarchical level of road asset is shown in Figure 6 and the different systems (level 2) are further described in the following subsections.

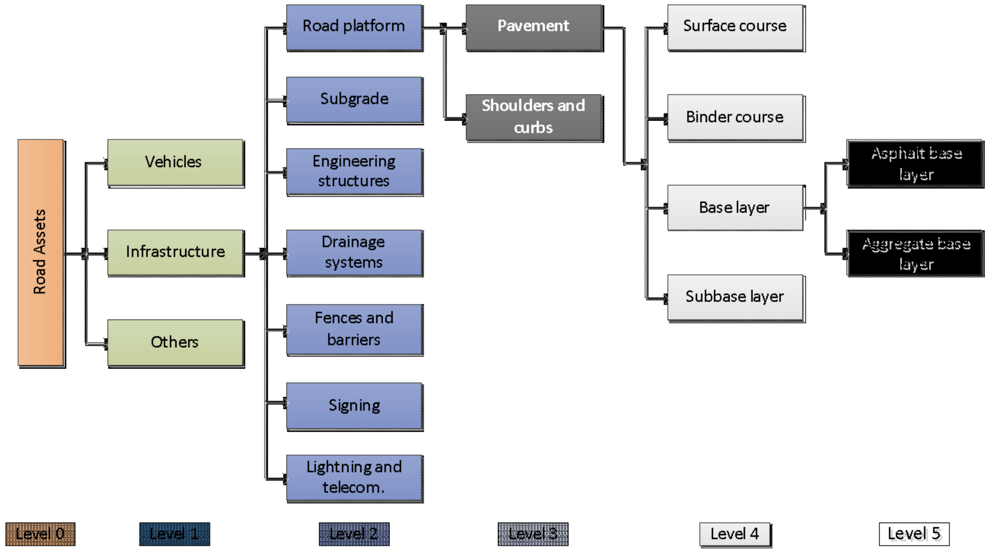

Figure 6: Hierarchical Representation Of Road Infrastructure

2.2.2.1 Road platform

Road platform is a non-linear asset and can be simply divided in pavement and shoulders (or curbs). However, in many cases, shoulders are constituted by the same materials than the pavement of the carriageway. Shoulders give the carriageway lateral support and may be used for emergency stops.

In general, the road pavement is a structure consisting of superimposed layers above the subgrade, whose main function is the distribution of the applied vehicle loads to the subgrade. Besides its structural role, road pavement should be able to fulfil several targets related to comfort and safety:

- An acceptable riding quality;
- Adequate skid resistance;
- Limited levels of noise.

2.2.2.2 Subgrade

Considering the subgrade, its primary functions are very like the ones found for railway:

- To offer the final support to the road platform;
- Bears and distributes the resultant load from the vehicles movement above the road platform;
- Facilitates drainage and provides a smooth platform, at an established grade, for the road platform to rest upon.

2.2.2.3 Engineering structures

Engineering structures are singular (non-linear) assets of road infrastructure such as bridges, viaducts or tunnels, even though in some cases they can have a significant length.

2.2.2.4 Drainage systems

Drainage is one of most important issues in the performance of road infrastructures as single failure can compromise by itself the overall road performance. The following targets can be identified for the road drainage system:

- Surface drainage (by draining the water away from the pavement structure;
- Limit the presence of water on the pavement surface, considering the aquaplaning risk and its effects on road safety;
- Erosion control (of the drainage system components).

2.2.2.5 Fences and barriers

Fences can have different purposes but in the most common cases are used to limit access to the road area, typically for higher hierarchy roads such as motorways. Barriers are primarily used for traffic separation, for instance in cross sections comprising different carriageways for each traffic direction.

2.2.2.6 Signing

The road signing system is categorized per the following classes:

- Road signs (instructions or information to the driver placed on the side or above the road);
- Traffic lights (for traffic control purposes);
- Road markings (instructions or information to the driver placed on the road pavement).

2.2.2.7 Lightning and telecom

Road lighting comprises many types of equipment, whose primary function is to provide lighting conditions in a linear basis along the road or for specific locations such as intersections, urban areas, bridges or tunnels.

Telecommunications should not refer to the driver aid systems placed along higher hierarchy roads, but also include the entire infrastructure supporting traffic monitoring and control systems or more complex Intelligent Transport Systems.

3 Condition information

For assessing the condition of a linear asset, different types of inputs and limits are required. This involves the geometric dimensions, material properties, operational or usage profile, external factors

and human factors. The outputs of this above list are fed to the inputs of WP4 and WP5 as listed in the features subsection.

An approach for implementation based on failure mode, mechanism, and effect analysis (FMMEA) is presented by Mathew et al. (2011) and depicted in Figure 7. The outline of this report also follows the flow of the approach. The design and material properties explored in previous chapter are put into a FMMEA resulting in the identification of failure models (see Section 4.1) and related critical failure and degradation mechanism (see Section 4.2). These are then used for the stress and damage modelling (component level) and finally the remaining useful life estimation, which here is the forecasting of the infrastructure geometry deterioration presented in Chapter 0.

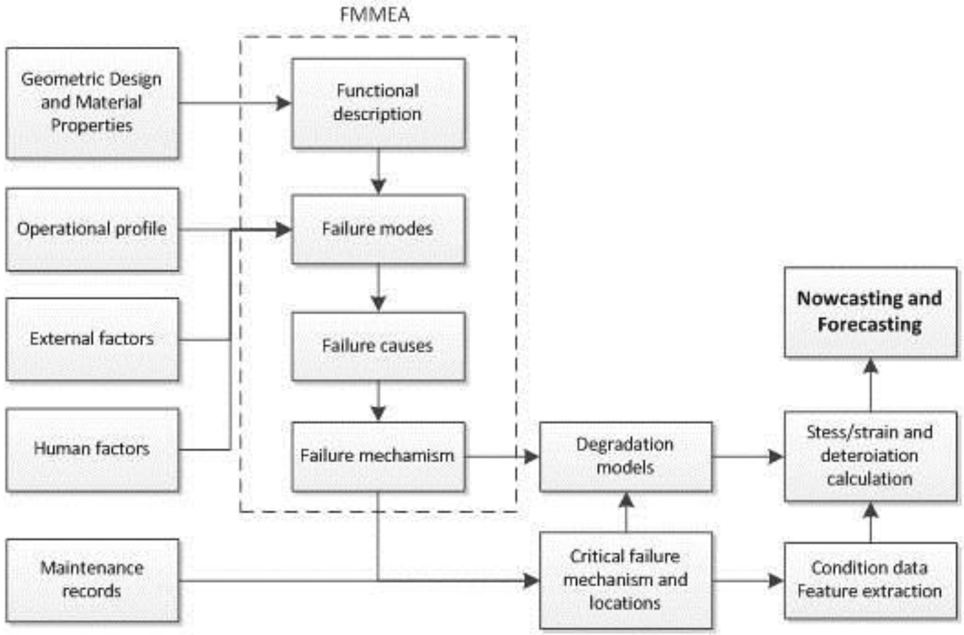

FIGURE 7: PHYSICS OF FAILURE BASED PROGNOSTICS APPROACH (MATHEW ET AL, 2011)

3.1 GEOMETRIC DESIGN AND MATERIAL PROPERTIES

From the hierarchical representation of Figure 3 and Figure 6, each asset is represented with geometric features. This includes the dimensions such as length, width, thickness sizes. The properties of the materials used are important to characterize the condition of the asset as its degradation behavior depends on the usage profile. The design and material properties of the critical assets in the hierarchical representation is briefed in this section.

3.1.1 RAILWAY

3.1.1.1 Superstructure: Track

The geometry quality of the track is defined as “assessment of excursions from the mean or designed geometrical characteristics of specified parameters in the vertical and lateral planes which give rise

to safety concerns or have a correlation with ride quality" (EN 13848-1). Listed below are the main geometry parameters used to assess track quality as shown in Figure 8.

- The ***track gauge*** is defined as the distance between the inner sides of the heads of the two rails, measured 14mm below the rolling surface (EN 13848-1). There are different types of gauges; standard gauge (1.435m), metric gauge (1.000 m), broad gauge (1.520m) and narrow gauge (0.914m).
- ***Alignment*** is the lateral deviation defined as a deviation in the horizontal direction expressed as a deviation from the mean horizontal position for various wavelength regions (EN 13848-1), see Figure 7.
- ***Cant*** (cross level) is the difference in height of the adjacent running tables computed from the angle between the running surface and a horizontal reference plane (Figure 7). It is expressed as the height of the vertical leg of the right-angled triangle having a hypotenuse that relates to the nominal track gauge plus the width of the rail head rounded to the nearest 10 mm (EN 13848-1).
- ***Twist*** is defined as the difference in cant taken at a defined distance apart, usually expressed as a gradient between the two points of measurement (EN 13848-1).
- The ***longitudinal level*** is the defined as the vertical deviation of consecutive running table levels on a rail expressed as an excursion from a reference line covering different wavelength ranges (EN 13848-1). This parameter is the principal determining factor for track degradation and track maintenance expenses (Profillidis, 2006).

The superstructure of the track consists of rails, sleepers, ballast and subballast, which design and material properties are described below.

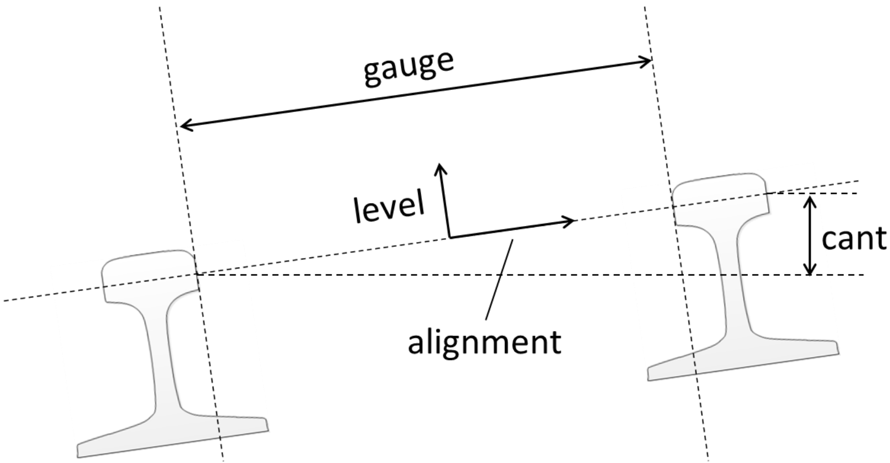

FIGURE 8: ILLUSTRATION OF TRACK GEOMETRY PARAMETERS (AFTER ESVELD, 2001).

Rails

All modern railways use steel rails for the required qualities of strength, fatigue endurance and wear and corrosion resistance. The geometric design of the rail is expressed in kg/m. A common rail is UIC60 with the rail size of 60 kg/m, and which shape and dimensions are depicted in .

The design of the head profile is designed dependent for curve radius. For example, on the Swedish heavy haul line, there are several rail profiles in use on the main track the dominant ones are 60E1, MB1 and MB4. MB1 and MB4 profiles are special designs that are derived from the standard UIC60E1 profile. Basically, these profiles differ at the gauge side, the MB1 have the largest gauge corner release, the 60E1 has the least, and the MB4 is between the two profiles. The main profile for tangent track is the MB4; curves with radius smaller than 650 m have the MB1 on the high rail and the 60E1 in the low rail. Figure 10 shows a sketch of the three profiles to point out some of the differences.

Concerning the chemical composition of the steel, rails present a great variety which will affect the material properties, e.g. shear and hardness, which are used as input features for the rolling contact fatigue and wear models further explored in Section 4.2.2

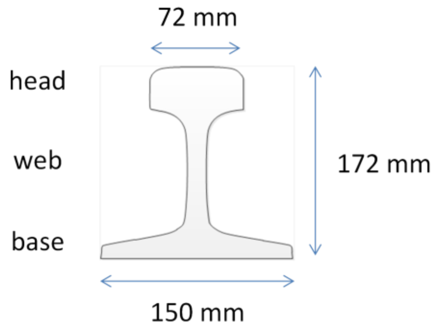

Figure 9: Cross Sectional Shape of UIC60 Rail

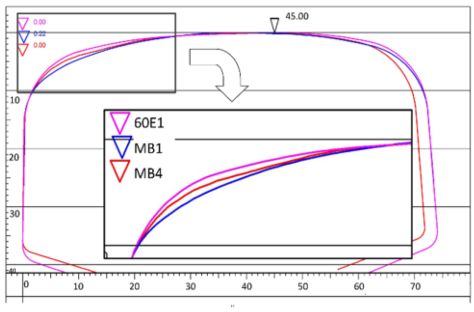

Figure 10: Different Rail Profiles That Are In Use On The Iron Ore Line.

Sleepers

Sleepers are the transverse ties that are laid to support the rails. They have an important role in the track as they transmit the wheel load from the rails to the ballast. Traditionally sleepers are made of wood, but restressed concrete is now widely used. The timber sleeper was accepted by most railways as standard up to about the middle of the twentieth century. Although its durability limitations were recognized, there are still many railways using timber sleepers due to the advantages of good resilience, ease of handling, adaptability to nonstandard situations and electrical insulation (Profillidis, 2000). The geometrical characteristics of timber sleepers are specified by the Worldwide Railway Organisation (UIC). Timber sleepers in standard gauge tracks have typical dimensions as shown in Figure 11.

The advantage of prestressed concrete is that tension cracks do not occur as the concrete is kept under compression under all conditions of flexure, both under load and after (Bonnett, 2005). Monoblock sleepers come in a large variety of geometrical configurations. All, however, are characterized by a reduction of the cross-section at the central part. The twin block sleeper consists of two reinforced concrete blocks joined together with a steel tie bar cast into the blocks. Figure 13 illustrates the geometrical characteristics of the twin block reinforced-concrete sleeper U41 of the French railways. Testing of concrete materials includes three steps to confirm acceptability: basic design, materials and finished product. The European standard describes in detail the steps for testing concrete sleepers: test arrangements and procedures, acceptance criteria, design approval tests, and routine tests.

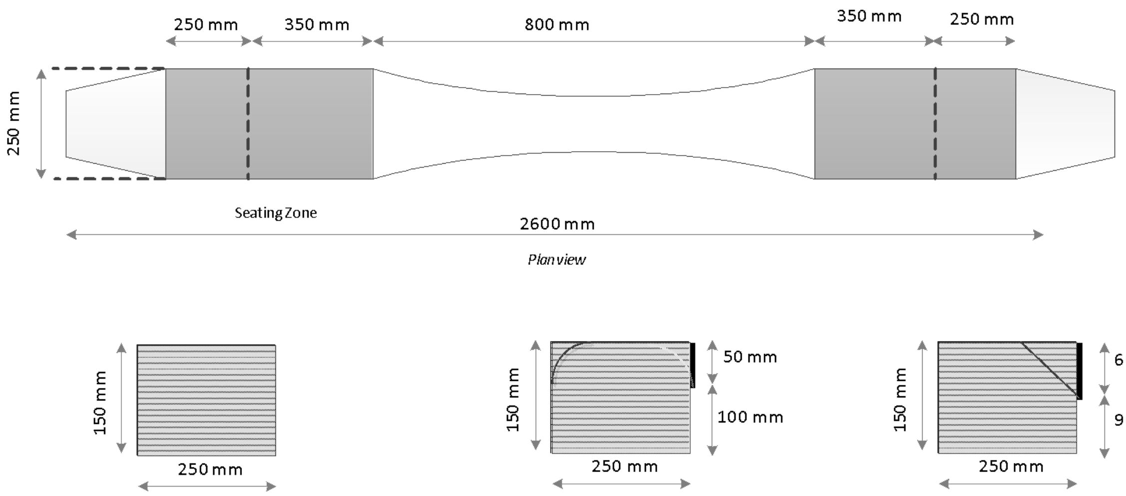

Figure 11: Sleeper Cross Section Forms (Profillidis, 2000)

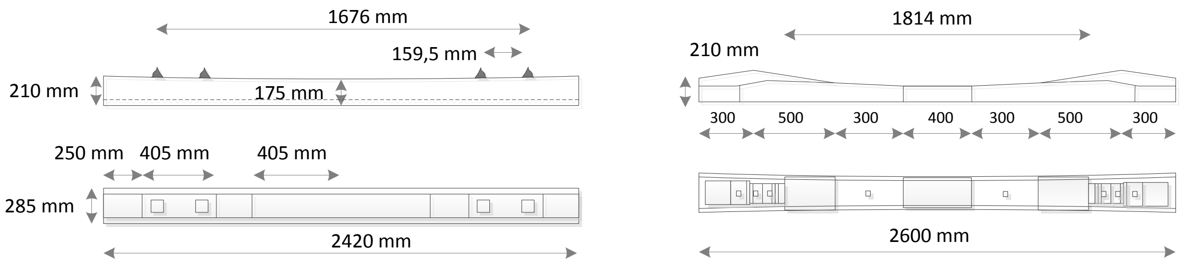

Figure 12: Monoblock Sleeper Of British Railways And German Railways (Profillidis, 2000)

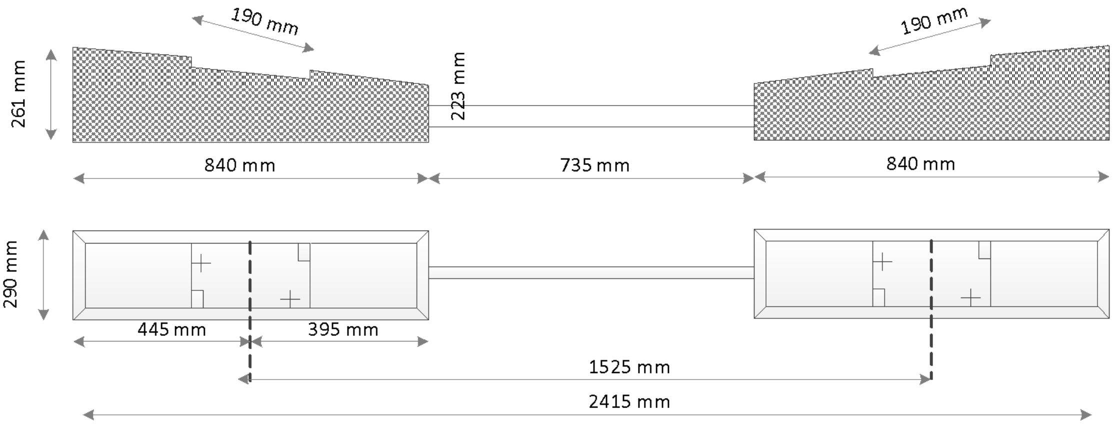

Figure 13: Twin-Block Reinforced-Concrete Sleeper U41 Of The French Railways (Profillidis, 2000)

Ballast

Good quality track ballast is made from crushed natural rock with particles not larger than 50 mm or smaller than 28 mm. Angular stones are preferable to naturally rounded stones, to achieve the best interlock properties and resistance to longitudinal and lateral movement under dynamic loading. If ballast particles are larger than the maximum size stated there may only be two or three stones between the underside of the sleeper and the sub-grade which will be scarce to properly distribute the load. Too many small stones below 28 mm will however clog the ballast and reduce, in the longer term, its drainage properties as given in Table 5. Samples of track ballast must be checked for grading by sieve analysis. Not more than 3% by weight should be retained on the 50-mm square mesh sieve and not more than 2% should pass through the 28 mm sieve and given in Table 6 (Profillidis, 2000). The shape and size of the ballast stones have a considerable influence on transverse track resistance as shown in Figure 14.

TABLE 5: BALLAST SIZE ACCORDING TO BRITISH REGULATIONS (PROFILLIDIS, 2000)

Sieze size D(mm)	Percentage to pass
63 mm	100
50 mm	97% - 100%
28 mm	0% - 20%
14 mm	0% - 2%
1-18 mm	0%-0.8%

TABLE 6: GRANULOMETRIC COMPOSITION OF BALLAST ACCORDING TO EUROPEAN STANDARD (PROFILLIDIS, 2000)

Sieve size (mm)	Railway ballast size 31.5 mm – 50 mm			Railway ballast size 31.5 mm – 63 mm		
	Percentage passing by mass					
	Grading category					
	A	B	C	D	E	F
80	100	100	100	100	100	100
63	100	97-100	95-100	97-99	95-99	93-99
50	70-99	70-99	70-99	65-99	55-99	45-70
40	30-65	30-70	25-70	30-65	25-75	15-45
31.5	1-25	1-25	1-25	1-25	1-25	0-7
22.4	0-3	0-3	0-3	0-3	0-3	0-7
31.5 – 50	≥50	≥50	≥50	-	-	-
31.5 – 63	-	-	-	≥50	≥50	≥50

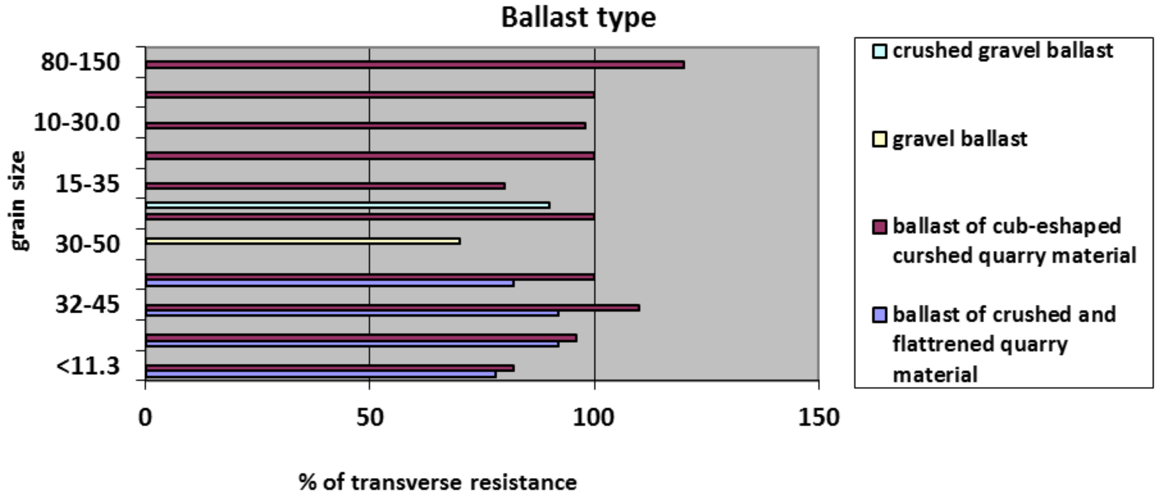

FIGURE 14: TRACK BALLAST TYPES AND ITS INFLUENCE ON TRANSVERSE RESISTANCE (AFTER PROFILLIDIS, 2000)

Rail Fastenings

There are three distinctive types of fasteners available (Profillidis, 2000)

- An elastic rail spike. This is driven into pre-drilled holes in sleepers and can be used with or without a steel or cast iron base plate.
- A spring clip bearing on the foot of the rail held down by a nut and bolt element tightened to a predetermined torque.
- A spring clip driven into a hole or slot in a 'shoulder', either cast into the sleeper or part of a base plate. The act of driving in the clip either twists or bends the clip thus creating a toe load on the rail.

3.1.1.2 Superstructure: Switches and crossings

Switches and crossings are non-linear assets of the railway and can be distinguished into three forms:

- Turnouts where the track is split in two or sometimes three.
- Crossings, where two tracks meet at grade with no change of course.
- Turnout crossings which is a combination of a turnout and a crossing.

A turnout, as shown in Figure 15, consists of (Bonnett, 2005; Nissen, 2009)

- main track and the turnout (or diverging) track, to which the vehicle can be diverted,
- mathematical (or intersection) point 0 of the turnout, which is the point where the axes of the two tracks intersect,
- frog angle, defined by the axes of the two tracks. The frog angle is commonly denoted by its tangent (e.g. 1:9). The frog angle consists of high-grade material (usually manganese steel),

- stock rail, which is the rail that stays motionless,
- switch or tongue rail, which is the moving rail which changes the course of the vehicle. A critical parameter is the radius of curvature R of the switch. Depending on their position, switch rails allow rail vehicles to proceed to one or the other track,
- check rail, which is a rail placed exactly opposite the frog. Shortly before the frog, a wheel reaches a rail gap and it is necessary to provide the other wheel with a guide bar preventing irregular and uncontrolled movement, which is achieved by installing a check rail.
- distances L1 (from the beginning of the turnout to the mathematical point) and L2 (from the mathematical point to the end of the turnout),
- turnout length L (L = L1 + L2),
- fouling distance c, which is the distance from the beginning of the turnout to the point beyond which a vehicle may lie on one track of the turnout without interfering with the movement of another vehicle on the other track. This point is specified so that the distance between the axes of the two tracks is at least 3.50 m for standard gauge tracks and 3.00 m for metric gauge tracks.

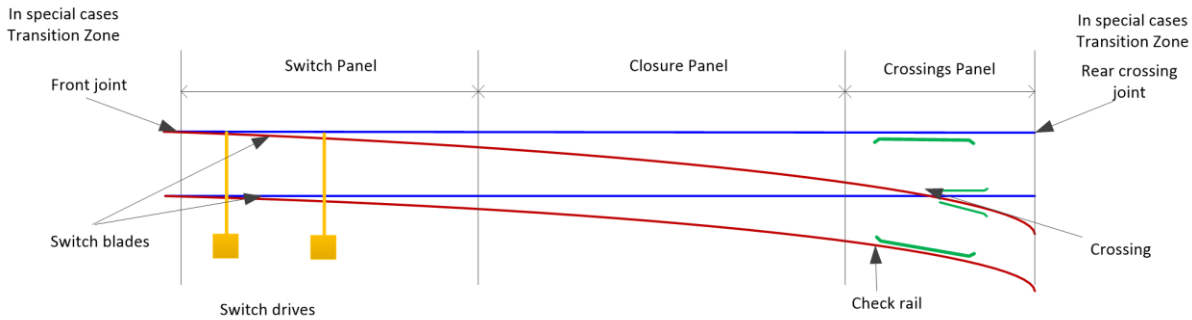

FIGURE 15: COMPONENTS OF A TURNOUT (NISSEN, 2009)

3.1.2 ROAD

Considering road pavements, there are two primary types of pavement surfaces — Portland cement concrete (PCC) and hot-mix asphalt concrete (HMA), being commonly named as rigid or flexible pavement, respectively.

Below this surface course other layers exist so that the entire pavement structure can support the traffic loads. These other layers, base and subbase layers can be made of granular materials or can be made of treated materials to enhance its structural capacity, including cement-treated, asphalt-treated or lime-treated layers. Additionally, and if there is a need, the subgrade can also be treated.

Considering HMA, as it is the most common pavement surface type across Europe, it consists primarily of mineral aggregates, asphalt cement (or binder) and air. The definition of the adequate proportions of each component is the known as the mix design process, based on the desired properties of the bituminous layer and expected performance. The performance of flexible pavements includes at least the ability to resist to three primary HMA distresses: permanent

deformation, fatigue cracking, and low temperature cracking. These distresses will be discussed further on.

The geometry design of road infrastructures is highly dependent on the road hierarchy, as the expected performance to a given road type will regulate the geometric features which should be considered in the design process. Nevertheless, these features allow that the safety, service and performance standards to be meet while the road is fitted to the topography of a given location. The following list includes the considerations which should be addressed for this purpose (Fwa, 2005):

- Design speed
- Design traffic volume
- Number of lanes
- Level of Service (LOS)
- Sight distance
- Alignment, super-elevation and grades
- Cross section
- Lane width
- Horizontal and vertical clearance

These considerations are set during the geometric design stage and have no influence on the future road condition, except if analyzed in the LOS perspective given different traffic volumes found when compared to design ones. Thus, for road components as pavements the condition is heavily dependent on material properties, operation profile and environment factors.

3.2 Operation profile

As mentioned above, the usage or operational profile of the load it gets experienced throughout its lifetime is vital for asset condition. This information is also useful to obtain nowcast and forecasting of the linear asset.

3.2.1 Railway

The operational profile depends on route length, journey time, train operation per each day, frequency of service in both directions, working hours during day, maintenance activities, traffic volume, dynamic axle load, speed and expected life of the asset.

3.2.2 Road

Considering road operation, one of the main causes of a road pavement performance below the expected condition, could be related to the less accurate estimation of the future traffic demand not only in terms of total number (Annual Average Daily Traffic) but also regarding the traffic composition. A higher actual heavy vehicle rate than the design one (as well as higher axle loads) will necessarily affect the pavement structure capacity while support the traffic loads.

3.3 External Factors

The condition of the linear asset varies with the location and accordingly, the external or environment factors, such as climate, affecting the asset also changes from time to time and place to place.

3.3.1 Railway

The less knowledge on the ground conditions of the infrastructure, inefficient way of resources and inability to monitor the infrastructure could lead to the more number of failures. The motive of the INFRALERT's "asset condition" can assist in the awareness of the infrastructure that ultimately reduce the number of failures in the infrastructure. One of the challenges is to monitor the environmental factors that lead to failures.

The work orders and maintenance actions believed that climate-related events are probably the one of the main reason for disturbances after technical failures (Baker et al., 2010). Even initial statistics of failures are more prominent in winter conditions in Swedish railway mainly due to the location of the railway track as show in Figure 16 for year 2008. The problems related with snow and ice on the track switches were the main cause by all sections that can cause failures and delays in the traffic.

The other major climate-related threats that can cause damage to infrastructure are high water levels from severe precipitation, high wind speeds and extreme temperatures. Especially, the major risk in warmer temperatures was the increase in failures of rail buckling. Railways are not only sensitive to the temperature conditions but also temperature gradient that can cause rail buckling and rail breakage (Dobney et al., 2009). Generally, the higher temperature difference in the successive time intervals can cause problems.

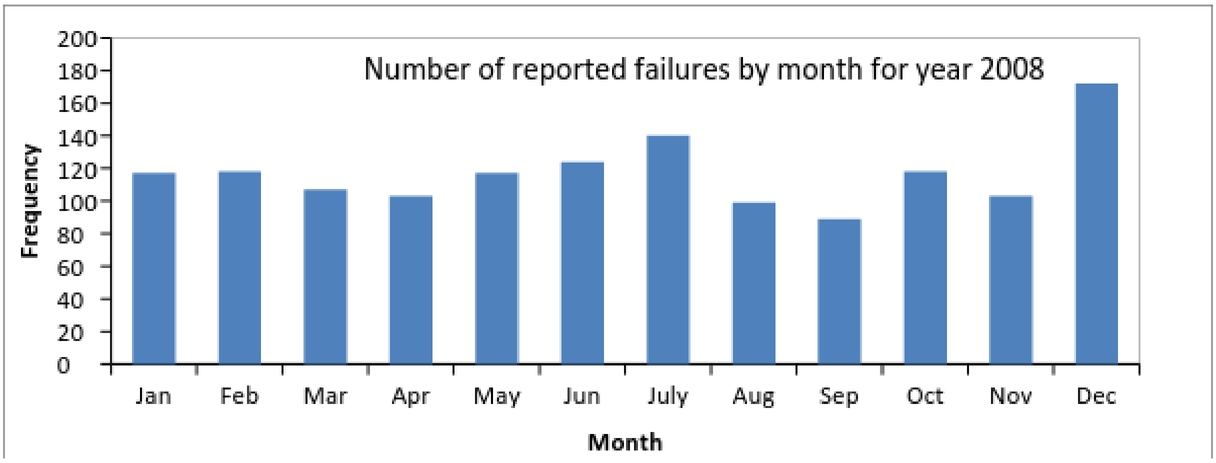

Figure 16: Number Of Reported Failures By Month For Year 2008

The power supply's disturbances due to changes in weather can directly effects the serviceability of the railway transport system. The other systems such as telecommunications and other transport systems could also effects the railway infrastructure due to weather fluctuations (Thomas and Davis, 2002). The heavier and faster trains can lead to more dry and stable ground conditions. Frequent movements in the track and the ground movements could also affect the tension in the rail and initiate rail buckling incidents (Kaynia, et al., 2000).

In some cases, the rail traffic might cause forest fires (Szczygiel et al., 2014). Hence, the type of vegetation in the rail corridor can also be considered as environmental factors. The electric equipment with fans is installed recently to keep the equipment functional in extreme heat conditions. In the future, the dependence on constant cooling of electronic and electrical equipment could make the railway infrastructure more vulnerable (Zhang et al. 2003).

In a different perspective, there are some positive consequences of climate change on anticipation of failures (Koeste & Rietvel, 2009), especially, in winter conditions (Palynchuk, 2013). From the Figure 16, there were fewer problems with track switches, train set doors and train engines in the transition periods but due to higher number of failures in winter, it is easier to predict the probability of failures. The main consequences of the failures are:

- limitations primarily due to delays
- disturbances because of less capacity and complete stops
- severe weather events making system breakdowns and severe accidents.

One can't neglect the less extreme consequences, such as minor delays in traffic, are in a way, useful for condition of the assets (Corman et al., 2010). Usually, there can be a chain of minor events behind that might lead to big incidents. In general, the warning systems possibly might not be installed on unknown locations for assessing the environmental effects, critically for the higher priority tracks. As discussed above, the variations in the conditions such as dry conditions followed by intensive precipitation might lead to unpredicted consequences for the railway systems. On such occasion is provided with an example.

During the summer of 2006, there was an incident in Ånn, due to exceedingly high rainfall over a small geographical area; the embankment was collapsed while a train was passing through. Initial investigations showed that the drainage system was functioning and it passed through the inspection. It was concluded that the technicians can have the better at highlighting the consequences, so that they can make the priorities correctly when conditions are changing. Due to the increase in the railway traffic and freight load, the probability of similar events will increase (Lindgren et al., 2009).

3.3.2 Road

Environmental factors can affect road performance in many ways. However, focusing on road pavements, the two main concerns are the water resulting from rainfall and the freeze cycles due to low temperatures.

When pavement surface fails in terms of its waterproofing function (typically associated to an advance degradation state), the entrance of water to the underneath layers may rapidly lead to an overall pavement failure to the change in the water content for these layers, compromising their performance. Additionally, in case of a failure of the surface water drainage system, the excess of water on the pavement surface during rainfall can heavily increase the accident risk.

Freeze cycles due to low temperatures can also affect the pavement performance as the water tends to expand in terms of volume, introducing additional stresses inside the pavement multilayer system which can lead to cracking.

3.4 Human Factors

"Human factors" is another term for ergonomics. It has traditionally focused on ensuring that employees have safe and easy-to-use equipment and a place in which they can work efficiently.

The timely application of human factors knowledge and techniques (RSSB, 2008):

- reduces the potential for error
- increases the margin for safety
- reduces the potential for expensive re-design
- increases the efficiency and effectiveness of training
- reduces the potential for expensive staff turnover
- increases the productivity of the whole organisation.

3.4.1 Railway

Even though railways are making impressive technological progress, maintenance remains challenging, and to be successful, a railway system must be well maintained. Maintenance includes a variety of collaborated technical fields, work orders, and personnel exposing to the multifaceted technologies (Oedewald and Reiman 2003). Maintenance in railways includes such activities as shunting, cleaning, graffiti removal, overhauls, effective management of spare parts and recycling of modules such as traction motors, wheels and bogies etc. Maintenance is a human activity. It is difficult to eliminate human errors but they can be reduced by better maintenance management procedures and better understanding of the issues that could affect these errors (HSE 2000).

The experts from the Human factors are also trying to create an appropriate framework for the analysis of the human factors in system reliability. The prime highlight is on the how to quantify a human error that reflects on a negative impact but also spans on varied conditions and events such as management decision errors, design and maintenance errors, and operator errors (Dekker 2004). In a complex infrastructure, as like in railways, there are several reasons of human errors for maintenance with varying degrees of order.

Researchers (Dhillon 2013; Peters and Peters 2006; Reason 2000) described that the most probable causes of human error as poor training, poor equipment design, complex tasks, poor work and design layout, poorly written maintenance manuals, inadequate work tools, poor verbal communication, poor management etc. As per (HSE 1999), three factor categories, job and organizational factors, affect the performance of any work activity, including maintenance. As of now, research has been conducted to measure maintenance performance (Parida and Kumar, 2006), human errors during operation and maintenance (Dhillon and Liu, 2006) and performance shaping factors by structural factors (Gertman et al., 2005).

To be precise, the human errors consider (Shappell and Wiegmann, 2012)

- individual factors like stress, fatigue, training, and certification
- job factors like work station design, maintenance manuals, and complexity of tasks, available time to diagnose problems, and available time to act
- organizational factors like role of management

The main dependent factors are ''Available time to diagnose'' and ''available time to act'' with weak driving power but strong dependence power. ''Stress'', ''fatigue'', ''complexity of task'' and ''fitness for performing the task'' have strong driving power as well as high dependencies and are linkage factors. If these factors are accommodated, there will be a positive influence on maintenance with a reduction in human error. Moreover, ''experience'', ''workstation design'', ''maintenance manuals'', ''training and certification'' and ''role of Management'' are independent factors. In other words, they have strong driving power and weak dependency on other factors. They may be treated as the key factors affecting the probability of human failure. It can be concluded that if the workplace layout, working posture, maintenance manuals and accessibility of equipment are not improved, maintenance performance is unlikely to improve (Singh et al., 2015, Singh et al., 2005a).

3.4.2 Road

Road maintenance encompasses a significant variety of activities considering the different level of system complexity. For example, routine maintenance consists of several actions to be undertaken on a regular basis to ensure the effective operation of the road infrastructure, such as crack sealing, patching or edge repair. Outside the paved area, other activities are also regularly needed such as clearing side drains and culverts, vegetation control, line-marking, the repair of road signs or safety barriers. All these road maintenance activities can also be associated to a higher level of complexity (and risk) as the road hierarchy and traffic demand increases.

3.5 Features (Output Variables)

Condition based maintenance modelling for road or railway can be simply divided into three components: input, process and output components. A simplified representation of these three components is shown in Figure 17. The selection of input variables into the model depends on the problem to be solved, characteristic nature and feature of the system and known behavior pattern, environmental consideration and usage profile of the system. The second component is the model estimation and calculation process. It involves the estimation of required parameter and constant using appropriate statistical concepts, physical theories for component failure and maintenance principle to ensure accurate estimation of the output feature.

The output feature is the 3rd component of condition based maintenance modelling. The type of output depends on the problem definition/objective of the model development. The problems be:

- Design, test or maintenance
- Condition forecasting or nowcasting

- Strategic, tactical or operational planning
- Operational safety or long term maintenance projection
- Understanding the failure mechanism of simple components or complex system
- Warranty estimation by component supplier or LCC estimation by asset owner.

The type of output feature also depends on detail level of the modelling procedure. In other words, the output feature can be:

- Direct measure of microstructure damage or dislocation at atomic level
- Measure of defect or damage at component level
- Time (calendar time, load or distance) remaining before functional failure at component or system level
- Aggregated health or integrity index of system or complex system

At the component level, the output feature can be a measure of the extent of defect such as wear, geometry deviation, profile variation, fatigue and size change (thickness, area or volume), mean of vibration, temperature. In instances when the definition of functional failure is given, the output feature can be time to reach the failed state, time to maintenance or remaining useful life. The use of time to functional failure as an output feature helps to simplify the development of maintenance decision support models. Finally, in some instances a derived health indicator or aggregated health indicator is used as an output feature. This integrity index could be an ordinal, interval or ratio scale depending on the modelling requirements and accepted practices on the modelled phenomenon. Indices commonly used in railway condition modelling include (see 5.1.1): wear index, rail damage index and track geometry deterioration, e.g. settlement. For road condition the road roughness and serviceability index are modelled, where the latter is a combination of the international roughness index and rutting (see 5.1.2).

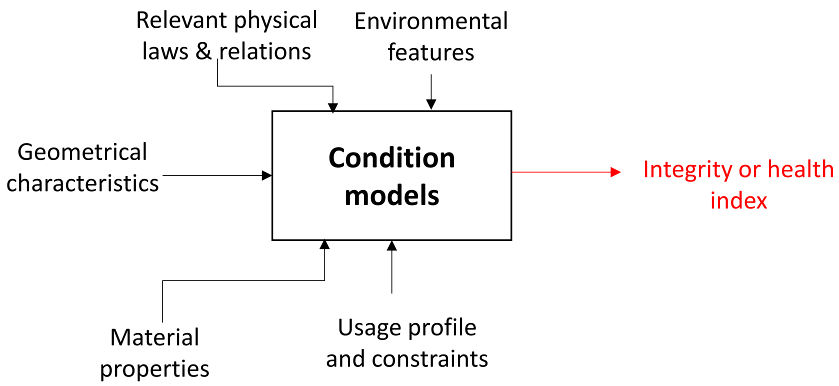

FIGURE 17: SIMPLIFIED REPRESENTATION OF CONDITION BASED MAINTENANCE MODELS SHOWING THE OUTPUT FEATURES

3.5.1 Railway

The different features required for alert management (WP4) are listed below per the categorization.

- Asset identification: In the hierarchical representation shown in Figure 3 (INFRALERT, 2016), the location of the asset is represented with both ancestor and descendent.
- Asset related features: The outputs of the sections from 3.1 to 3.4 (INFRALERT, 2016) are the features related to the railway assets.
- Asset Historical Maintenance interventions: It consists of two types of information; lexicographic (maintenance limits, cause, type of failure, operations, restoration and resources required) and categorical to assess the soundness condition at the end of intervention for an asset in the infrastructure.
- Asset Condition assessment and predictions: The nowcast and forecasted condition of the infrastructure from the relevant features that triggers the auscultation measurement, visual inspections, maintenance interventions and exogenous information.
- Features related to RAMS Analysis consist of time to failure data including repair and waiting time extracted from work orders.

3.5.2 Road

Currently, WP4 considers as inputs the following:

- Road condition
- Measurement campaign
- Road geometry parameters
- Parameters thresholds

At the same time, historical maintenance interventions undergone on any of the infrastructure assets are also included. The related interventions on the road case are stored in table named Road intervention and the associated fields of this table are described in separate tables within the Data Farm:

- Intervention lane
- Intervention type
- Type of work
- Type of material

Regarding the information about asset condition assessment and its predictions, as stated on D4.1 (INFRALERT, 2016) and per the existing and recorded information, it is expected that WP3 will provide the current and forecasted condition of any asset of the infrastructure referred to the relevant variables (features). Asset condition (nowcast and forecast) should be updated when any feature suffers a modification:

a) a new auscultation measurement;

b) a new visual inspection that incorporated information into the system;

c) maintenance interventions which incur in alteration of any asset condition;

d) new update of any exogenous feature (e.g. the course of time is sufficient to obligate to an update by re-executing the eIMS).

The forecasted condition will be estimated for those (further) scenarios previously defined by WP6 (i.e. operational, tactical and strategic), respect to the time stamp when the query takes place.

4 Degradation Mechanisms

4.1 Failure Modes

Failure mode is the inability of an item to perform a required function. It is also referred to as all events that cause functional failure. The failure modes of a system are often related to its material properties, operation (usage condition), environment, structure, dimension and design feature/defects and other system peculiarities. Human errors caused by operators or maintainers can also be considered as failure modes of a system.

It is not only essential to carry out a detailed mapping of the functional condition of linear systems at different hierarchical level, but also equally important to identify the possible failure modes. This will help us to know which failure is critical and require condition monitoring. The prediction can be carried out by obtained by condition monitoring data for nowcasting or forecasting. Below are some failure modes in both railway and road infrastructure that are relevant for forecasting.

4.1.1 Railway Track

The main function and failure mode of major components of track (linear asset) and switch & crossings (non-linear assets) are summarized in the Table 7 and Table 8.

Table 7: Failure Modes For The Railway Track

Assembly/ Component	Function	Failure mode	Failure effect on system
M1. Track			
M1.1 Rail	Running surface, Guidance of train wheel, wheel load transfer to sleeper without deflection	Uneven running surface (corrugations and skid marks)	Increased dynamic effect and vibration, failure of other components, impaired ride comfort
		Indentation	Reduction of loading capacity, distortion of rail profile, accelerates other failures, discontinuous area
		Corrosion	Discontinuity, local rail weakness, rail breakage, potential for derailment
		Rolling contact fatigue	Rail breakage, potential for derailment,
		Out of profile (wear)	Wheel climbing, wheel roll-over, operational effects

M1.2. Sleeper	Receiving and distributing load over supporting ballast, maintaining track gauge & position, restraining lateral, longitudinal and vertical rail movement by anchorage of the superstructure in the ballast	Cracks	Poor distribution of load, damage to other elements,
		Concrete damage	Poor load distribution, damage of other components
		Wooden sleeper twist, decay, ageing, widening of fastening hole	Potential for gauge widening, contribution to poor later track resistance.
		Displacement	Reduction of loading capacity and potential for derailment
M1.3. Fastener	Elastic fixation of the rail on the rails on the sleeper, take up horizontal forces	Removal, breakage, Loosening.	Gauge change and instability of rail position, possible derailments in case of several breakages
M1.4 Joint	Insulation of rail, provision of expansion possibility	Damage, bond failure, loosening, crushed end posts, delamination of end post, broken joint bars	Isolation and train position problem, risk of train collision, discontinuous area,
M1.5 Ballast	Distribution of load, absorbing shock from dynamic load, anchor the track and drainage function	Contamination	Poor water run off, poor track stiffness, bad geometry and load carrying capacity
		Breakage and formation of too many fines	Penetration into subgrades and Settlement
		Lack of consolidation	Poor lateral resistance and potential for buckling
		Depletion, displacement	Poor distribution of loads, hanging sleepers, operational effect.
M1.6 Baseplates	Fastening of the rails, distribution of load	Breakage	Load increase on nearby plates, gauge change, multiple plate breakage is a potential for derailment
M1.6 Pads and mats	Reduction of ground & air borne vibration and noise. Improvement of stiffness at transition zones and other critical zones.	Ageing, damage, contamination	Noise, reduction of ride quality and increase in environmental impacts

TABLE 8: FAILURE MODES FOR THE RAILWAY S&C

Assembly/ Component	Function	Failure mode	Failure effect on system
M2. S&C			
M2.1 Switch and stock rail assembly	Enabling vehicles to pass from one track to another by selecting the route.		

M2.1.1 Stock rail	Supporting closed rail and wheel guidance for open blade. Receiving and distributing load over supporting ballast	Cracks, bad rail head profile, cross breakage	Potential for derailment, noise or reduced ride quality
M2.1.2 Distance blocks	Horizontal support of switch blade and taking up of forces	Breakage	Increase of the switch strain, potential for derailment with other failure modes
M2.1.3 Anti-creeping device	Limiting the relative movement between switch and stock rail due to thermal displacement	Element breakage	No effect on system besides adjusting problem
M2.1.3 Switch rail	Guidance to moving wheel, receiving and distributing vertical and horizontal forces	Rail cross breakage in the front or back side	Wheel climbing, potential for derailment, operational effect (speed restriction)
M2.2 Crossing	Enabling smooth passage of wheel by providing with a gap in front of the nose. Receiving and distributing track forces	Deformation, cracks, breakage	Discontinuous area, increase in strain, wrong guide function, potential for derailment,
M2.3 Check rails	Prevention of the wheel flange from running against the tip of the crossing. Guiding the wheelsets safely over the crossing gap	Change in profile and size: too small or too large, breakage	Damage of crossing nose, wrong guide function, potential for derailment
M2.4 Running rails	Receiving and transferring loads	Cracks, out of profile (wear), corrugations, rail breakage	Reduction of loading capacity, distortion of rail profile, discontinuous area, possible noise and poor ride quality
M2.5 Slide plates	Fastening of the stock rails, enabling sliding of the switch rail. Distribution of forces	Breakage	Change of gauge, adjustment problem, possible interference in operation
M2.8 Base plate pads	Protection of the track bed, adsorption of vibration and noise, insulation of rail	Ageing, contamination damage	Plate impact with track bed, noise and poor ride quality, potential for train collision due to insulation failure
M2.6 Fasteners (clip)	Elastic fixation of the rail on the base plates	Loss of contact, breakage	Gauge change and instability of rail position, possible operational interference
M2.7 Rail pads	Stiffness enhancement, Absorption of vibration and noise, insulation	Ageing, damage, contamination	Noise, reduced ride quality and potential for train collision
M2.8 Sleeper	Same as in Track		
M2.9 Ballast	Same as in Track		

Note: Electrical and electronic components of S&C such as actuator, detection device, locking device and the control units are not included in this description.

4.1.2 Road

Regarding flexible pavements, different types of stress can occur because of each of the following factors or any combination between them:

- Traffic load repetitions;
- Temperature;
- Moisture;
- Materials' aging;
- Construction practice.

Regarding a pavement, ageing tends to be limited to flexible pavements where the ageing process of the bitumen can lead to the change of its rheological properties, for instance, hardening with a loss of elasticity. The different failure modes for road are shown in Table 9.

4.2 Critical Degradation Mechanism

Prior to the development of nowcasting and forecasting models it is very important to understand the physical mechanisms that are at play and have significant influence on the degradation process and failure events of linear infrastructure. The mathematical models for some of these critical failure mechanisms are given in the next chapter.

4.2.1 Geometry Deterioration

An important aspect of road and railway engineering is the geometry deterioration. It is of significant requirement in the design, construction, installation and maintenance.

Table 9: Failure Modes For Road

Assembly/ Component	Function	Failure mode	Failure effect of subsystem
Pavement	Provide an adequate skid resistance	Loss of skid resistance	Functional failure (safety)
	Provide an adequate riding comfort	High level of unevenness (due to other distresses)	Functional failure (comfort)
	Structural support and load distribution	Fatigue cracking	Structural failure
	Structural support and load distribution	Low-temperature cracking	Structural failure
	Structural support and load distribution	Permanent deformation	Structural failure
Subgrade	Structural support and load distribution	Permanent deformation	Structural failure

4.2.1.1 Railway

The geometry of the track has four degrees of freedom of both rails. This geometrical characteristic of the track is defined using principal parameters that are measured in relation to the coordinate system which is centered to the track. The parameters include: longitudinal level, alignment, cross level, gauge and twist (see 3.1.1).

Geometry deterioration is a complex phenomenon that proceeds under loading and unloading traffic cycle that results into both elastic and plastic deformation. After the initial settlement, a gradual progression of the geometry quality with time or tonnage is seen and then followed by rapid loss of quality due to ageing of the track. The three phases of geometry deterioration of the track follow the distinct phases of a bathtub curve describing the hazard rate in reliability engineering (see Figure 18). The initial phase, infant mortality phase of hazard function, settles though rapid, is unpredictable and short in length, thus it is mostly neglected in modelling process. At this stage, initial voids are filled and ballast memory is restored. The second phase is gradual and it represents the useful life of the track, basically this is the phase that is modelled since the track is stable and deteriorates steadily. The last deterioration phase is rapid, representing a wear out stage when the track components such as rails, sleepers, fasteners, ballast or subgrade are irreversibly destroyed. This stage should not be allowed since it is a threat to safety of traffic and reduces the life span of track structure as well as its technical performance. Geometry deterioration or differential track settlement is caused by several mechanisms of ballast, subgrade compression and inelastic deformation under traffic load. Predominant among these are volume reduction due to ballast and subgrade particle rearrangement, sub-ballast or subgrade penetration into ballast voids, particle breakdown from train loading and abrasive wear at points in contact with other particles.

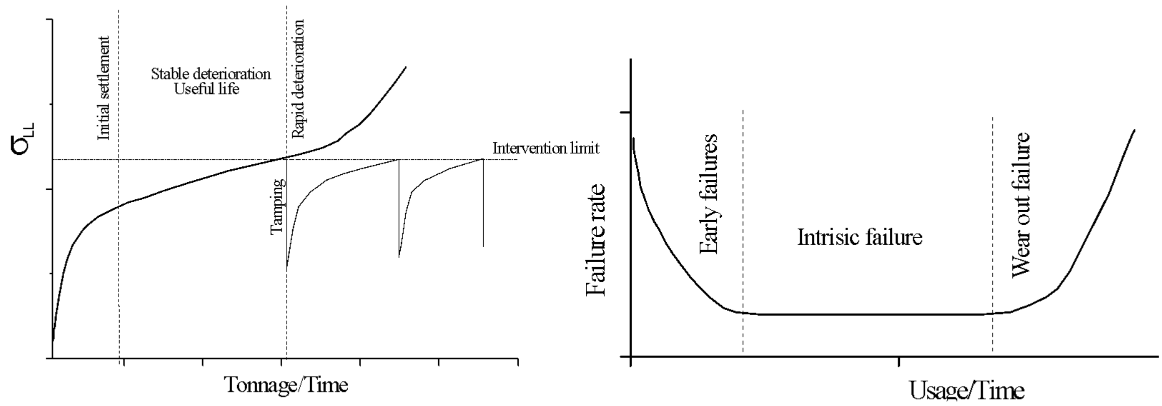

FIGURE 18: PHASES OF DETERIORATION WITH TIME COMPARED WITH BATHHUB CURVE (FAMUREWA ET AL, 2013)

4.2.1.2 Road

For flexible pavements, stress resulting from traffic loads could derive in several degradation mechanisms. One of the most common is permanent deformation, corresponding to the plastic deformation of bituminous layers under repeated loads. Permanent deformation can be present in two different forms (Fwa, 2005):

- Rutting (lateral plastic flow in the wheelpaths) which will lead to transverse unevenness and could compromise safety due to the potential of water concentration inside the rut;

- Consolidation (increased compaction of the bituminous mixture).

4.2.2 ROLLING CONTACT FATIGUE (RCF)

The low rolling resistance of wheel and rail is achieved using materials with high modulus of elasticity that limits the contact area bearing the heavy load. The consequence of this finger nail size area under heavy load is high stress which can be higher than 1000 KN/mm^2. This can lead to plastic deformation of the wheel and rail, surface and new-surface cracks. Cracks are initiated if the stress on the material in the small contact area exceeds a certain level under repeated and combined application of tangential forces (slip, braking and acceleration forces) and high vertical loads. This behavior called ratcheting is the aggregate expansion occurring during individual cycles when wheels pass over the rail in a cyclical loading regime. As shown in Figure 19, if the stress is below the elastic limit, no plastic deformation occurs. Continuation of the cyclic loading of the rail leads to increase in stress and high strain hardening without plastic deformations (i.e. elastic shakedown). Further increase in stress will then lead to plastic deformation which does not progress as the loads are cyclic (i.e. plastic shakedown). As the stress grows, every subsequent cycle will cause further plastic deformation and eventually lead to cracking. In order words cracks are initiated because of the accumulation of strain energy in the material from the forces generated at the wheel/rail interface. These forces are generated in both the vertical and shear (longitudinal and lateral) directions and arise due to the steering behavior of the vehicle's wheel sets.

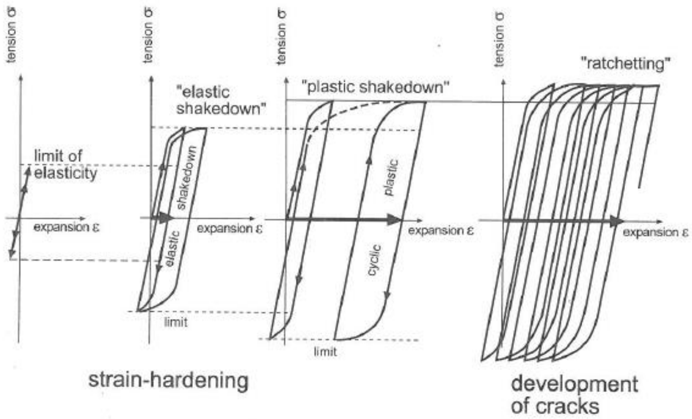

FIGURE 19: STRESS AND FATIGUE DIAGRAM UNDER CYCLIC LOADING (LICHTBERGER, 2005)

The development of RCF in curves has been attributed to the type of rolling contact that is probable depending on the radii of the curve. The development could be any of the three different modes shown in Figure 20, i.e. the 1-point contact, the 2-point contact and the conformal contact. A study carried out by one of the European infrastructure managers has reported that rolling contact defects occur most frequently in the radii range of 1200-2000m on their rail network, see Figure 20. The widest seen defects due to RCF are squats and head checks.

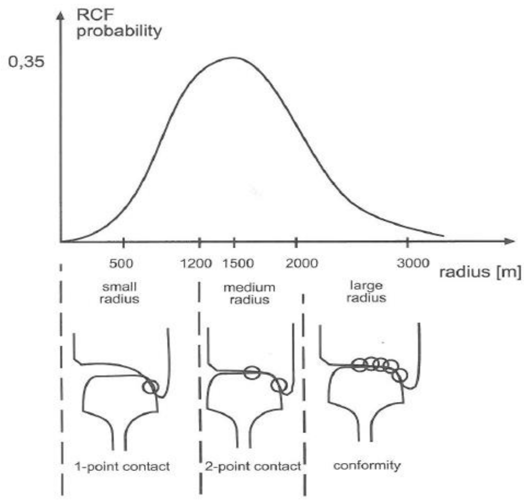

FIGURE 20: PROBABILITY OF RCF DEVELOPMENT AS A FUNCTION OF CURVE RADII (LICHTBERGER, 2005)

4.2.2.1 Railway

For tracks with wide curves, RCF is much more relevant than side-wear. The degradation rate (crack depth growth rate) is influenced by

- Traffic volume
- Axle Forces (slip, esp. Locos)
- Radius
- Rail Steel Grade

RCF failures can be identified with eddy current measurements.

The multiple changes of compression and tensile stresses may cause an exceeding of the fatigue resistance. This process is triggered by ·

- Traffic volume
- Axle Load Distribution
- Rail Profile
- Temperature

4.2.2.2 Road

Besides permanent deformation, cracking is the other primary degradation mechanism because of the stress associated to traffic loads. Cracking can then be divided in two categories (Fwa, 2005):

- Load associated cracking which is commonly known as fatigue cracking, due to the repeated stress applications below the maximum tensile strength of the material;
- Non-load associated cracking, such as low-temperature cracking. When rapid cooling and low temperatures are present, the stress experienced by the bituminous mixture can eventually exceed its fracture strength, leading to cracking initiation.

4.2.3 WEAR

Wear is the loss or displacement of material due to the abrasive action of the rolling wheel on rail (or road) during interaction. The wear of road and rail is of great interest since it is known to be an important degradation mechanism that can limit their functional performance, reduce system life span and significantly increase system life cycle cost if not well managed. It is connected to the complex stress environment of the asset. For example, railway track is prone to wear as a result of the combination of contact stress, bending stress and thermally induced stress.

4.2.3.1 Railway

Wear of rail is directly related to wheel-rail interaction in terms of the load, complex stress field and configuration of the contact. The main wear mechanisms in wheel-rail sliding or rolling contacts are adhesive, abrasive, fatigue driven, thermal and oxidative wear processes. Further, rail wear occurs at the top of the rail as head (top) wear, or at the side as gauge face wear or can be described to occur in the form of combined head and side wear. Wear area is another measure of wear in terms of material loss or displaced at the head area in relation to a reference profile. The profile of rails under heavy traffic condition gradually change owing to wear, contact fatigue cracks and plastic flow because of high contact stress as shown in Figure 21. The key factors that affect the rate of rail wear from literature include: track curvature, layout, rail grade, metallurgy, profile, train speed, wheel profile, axle load, traffic characteristics, lubrication, contaminations and other environmental conditions.

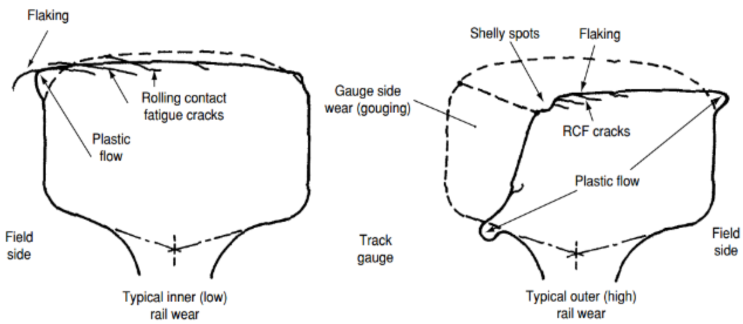

FIGURE 21: WEAR, RCF CRACKS AND PLASTIC FLOW OF RAILS IN CURVES.

4.2.3.2 Road

As mentioned before, wear as critical degradation mechanism is associated to functional failures. Because of the tyre-pavement interaction, the bituminous mixtures aggregates start to get polished aggregates, causing in the loss of texture, either microtexture (skid resistance) or macrotexture. In both cases, road safety issues can arise.

5 Mathematical and statistical model

The condition information, whether it is the current state (nowcasting) or a prediction of future state (forecasting), can be obtained mainly using one or more of the following three modelling approaches: Physics-based, Data-driven, and Knowledge-based. These models can be used for "Asset Condition" of the linear assets. "Asset Condition" can be connected to other toolkits related to the INFRALERT project is shown in Figure 22.

All three approaches make use of condition data, whereas data-driven is the approach that rely almost entirely on condition monitoring data. Linear asset condition information will be useful only if treated in a way so that each segment is allocated with a meaningful value. Typically for degradation modelling related to maintenance planning for railway and road infrastructure, the input to models is time series of geometry data. Segmentation is important in order to establish these time series and to follow the trend over time. Segmentation is also important to integrate condition monitoring time series data with other relevant information such as asset data, maintenance records, and weather information. This is important for the implementation of models.

One approach is to divide the section/network into several equally long segments, e.g. 100 m for road longitudinal unevenness (IRI) and 200 m for railway geometry such as longitudinal level. Another approach is to divide the asset into homogenous segments. This can be accomplish using static asset features, such as geometric design, material properties, operational profile and other external factor as described in previous sections. An alternative is to use dynamic segmentation. For dynamic segmentation, the linear asset is divided based on the measured condition, which hence is dynamically changing over time. An example is the AASHTO cumulative difference approach for dividing road infrastructure into statistically homogenies segments (Appendix J; Aashto, 1993). For other approaches for homogenous sections and segmentation see Thomas (2003, 2005), Mishra & Das (2007), and Cafiso & Di Graziano (2012).

5.1 PHYSICS-BASED MODELS

Models play an important role in addressing a variety of problems in linear infrastructure management. A model is a representation of the real world that is relevant to the problem. There are many different types of models. Some of these are physical models and others abstract. In most cases, modelling requires mathematical representation of the process involved using a mathematical formulation. When uncertainty is a significant feature of the phenomenon or process to be modelled, then concepts from probability theory and statistics play an important role in linking the model to reality.

Physics-based approaches focus on the load of traffic since a large part of infrastructure degradation depends on the load of every axle passage. When the material is subjected to heavy loads it deforms and the deformation depends on the magnitude of the stresses and/or strains the material is exposed to. The modelling is done on component level (cf. the linear asset modelling hierarchy in Figure 1). For system level, it is difficult to determine the resulting deformation (geometry deterioration) even if the load can be determined. Therefore, empirical data are necessary for physics-based approaches. As previously discussed, physics-based models are therefore mainly considered for design purposes. Examples of such wear and rolling contact fatigue models for railway are described in 5.1.1. The focus of this section lies in road and track geometry deterioration models that are used for the forecasting of asset condition and decisions support for maintenance planning.

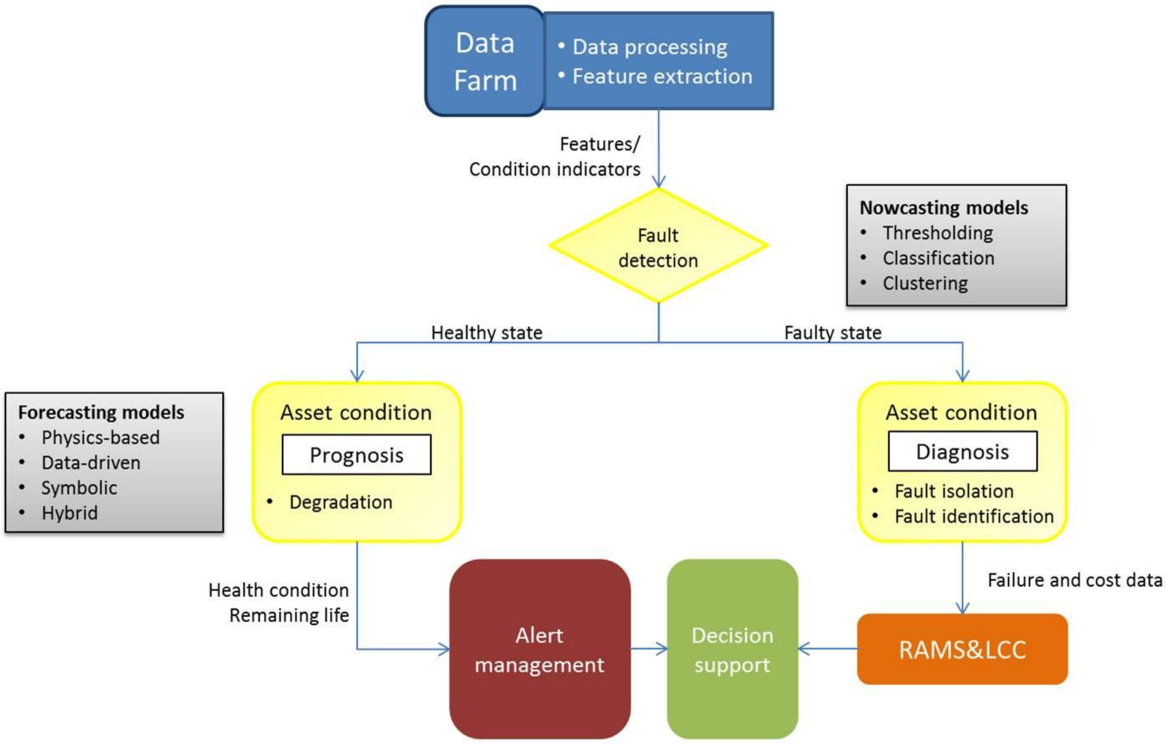

FIGURE 22: TOOLKITS OF INFRALERT

5.1.1 RAILWAY

Track degradation, as in fatigue of rail and settlement of track, is largely determined by the force amplitudes excited by a passing wheel set. The loads from a single pair of wheels can be divided into three components:

- Static wheel load
- Quasi static wheel load at curves
- Dynamic contribution due track or wheel irregularities

The static and quasi-static parts of the load are often relatively easy to derive. For the dynamic contributions various empirical relationships have been developed (ORE, 1988; Demharter, 1982; Andersson and Stichel, 1999).

The following section will give examples of physics-based models on component level for rail and sleeper, and thereafter track geometry models will be described.

5.1.1.1 Rail

Rolling contact fatigue

Ekberg and colleagues have developed models for rolling contact fatigue (Ekberg et al., 2002). Surface fatigue is expressed as

$$FI_{surf} = \mu - \frac{1}{\nu} = \mu - \frac{2\pi abk}{3F_z} > 0 \quad (1)$$

where μ is the friction, a and b the semi-axes in the Hertzian contact, k is the yield stress in shear, and F_z is the magnitude in vertical load. Surface fatigue is predicted to occur if the index is greater than zero. From the index various preventing actions can be identified (Ekberg and Kabo, 2005):

- increase the material contact geometry (a, b) by e.g. grinding of rails, and surface coating and rim quenching of wheels
- decrease the acting frictional loads (μ) by lubrication

The index for subsurface fatigue is based on Dang Van et al. (1989) and can be approximated as (Ekberg et al., 2002)

$$\mathrm{FI_{sub}} = \frac{\mathrm{F_z}}{4\pi \mathrm{ab}}(1+\mu^2) + \mathrm{a_{DV}}\sigma_\mathrm{h} > \sigma_\mathrm{e} \quad (2)$$

where a_{DV} is a material parameter, σ_h is the hydrostatic part of the residual stress. Subsurface fatigue is predicted to occur if the index is greater than the equivalent fatigue limit σ_e, which normally is taken as the material's fatigue limit in shear (Ekberg and Kabo, 2005).

Wear

Wear is a complex process that involves several modes of material deterioration and contact surface alteration (Enblom and Stichel, 2010). Various wear models have been developed and used for the assessment of how different track and wheel geometry configurations affect wear, especially for different curve radius. Based on Archard's wear model (Archard, 1953), the wear volume is proportional to the product of the normal contact force and sliding distance (s) and inversely proportional to the hardness of the softer material (H). For a contact area (slip zone) the wear depth $\Delta\varsigma$ can be expressed as (Jendel and Berg, 2002; Enblom and Stichel, 2010)

$$\Delta\varsigma = \mathrm{k}\frac{\mathrm{p}\Delta\mathrm{s}}{\mathrm{H}} \quad (3)$$

where k is the wear coefficient and p is the contact pressure. Alternatively, a commonly used wear index is based on the dissipated energy in the contact area. At KTH (Stichel, 2004), a simplified wear model has also been developed as function of the curve radius and the vehicle radial steering ability (k_b), as depicted in Figure 23.

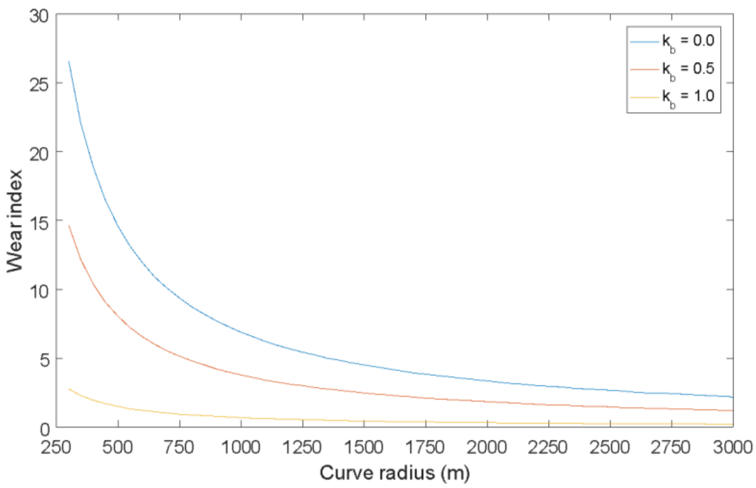

FIGURE 23: AMOUNT OF WEAR DUE TO CURVE RADIUS AND VEHICLE RADIAL STEERING ABILITY (KB) (STICHEL, 2004)

5.1.1.2 Sleeper

The replacement of sleepers is general predetermined based on load e.g. using k or of m reliability analysis. An example of a physical model of the degradation of timber sleepers has been developed at the University of Kingston (Larsson, 2004). The model describes the degradation due to traffic and sleeper age. Wheel loads generate stress (σ_i) into the sleeper. Based on a standard loading cycle of a wheel (σ_{std}), an equivalent number of standard axle ($N_{i,eqv}$) can be derived as :

$$N_{i,eqv} = N_i(\frac{\sigma_i}{\sigma_{std}})^{k_t} \tag{4}$$

where k_t (damage intensity factor) is calculated as the product of a sleeper age factor, drainage factor, and decay intensity factor determined based on external factors such as climate (Larsson, 2004). The concept of the model is like the calculation of equivalent standard axles (ESAL) used for road geometry deterioration described in 5.1.2.

5.1.1.3 Track geometry

There are several different models of track geometry deterioration or settlement. As previously discussed, all these models are also more or less empirical. The knowledge about the actual mechanisms behind the deterioration is still unknown (Dahlberg, 2002; Stichel, 2004).

The track geometry deterioration model suggested by Office de Recherches et d'Essais de l'Union Internationale des Chemins de Fèr (ORE, 1988) is one of the commonly applied models. The deterioration model as given in equation (5) below accounts for two phenomena: the deterioration directly after maintenance (tamping) e_o and the traffic induced deterioration. The second part depends on traffic volume T, dynamic axle load Q and speed v.

$$\mathrm{e} = \mathrm{e}_0 + \mathrm{h}\mathrm{T}^{\alpha}(2\mathrm{Q})^{\beta}\mathrm{v}^{\gamma} \tag{5}$$

where h is a constant and the parameters α, β, and γ must be estimated from experimental data. This model can be adapted to give the kind of outputs that is useful for the requirements of INFRALERT. Given a specific operational history of a railway section, the remaining axle load or traffic volume that should be anticipated before reaching a predefined intervention or alert threshold can be estimated. The remaining traffic volume to reach the threshold is referred to as remaining useful life and can be used for alert management and maintenance planning.

Another model developed by Sato (1995) in Japan describes the settlement (y) as a function of repeated number of loading or tonnage carried by the track (x) as

$$\mathrm{y} = \gamma(1 - \mathrm{e}^{-\alpha \mathrm{x}}) + \mathrm{bx} \tag{6}$$

where α, β, and γ are constant extracted from experiments.

A model for the settlement has also been developed at TU München (Demharter, 1982) based on the log of number of axle passes (N) and ballast pressure (p) given in below equation. The ballast pressure is calculated using the Zimmerman method (Eisenmann, 1969).

$$\mathrm{S} = \mathrm{a} \cdot \mathrm{p} \cdot \ln{(\Delta \mathrm{N})} + \mathrm{b} \cdot \mathrm{p}^{1.21} \cdot \ln(\mathrm{N}) \tag{7}$$

The first term represents the fast settlement after maintenance (tamping) where ΔN is the first passing axles during a pre-loading period. The constant a is between 1.57 and 2.33 and b is between 3.04 and 15.2.

5.1.2 Road

For road, AASHTO Road design guide is a commonly used model. The properties of the base and subbase are described by a structural number, which is a function of the thickness and modulus of each layer and the drainage conditions. From the model, number of equivalent single axle load (ESAL) that the road tolerates can be extracted, i.e. total ESAL to pavement failure. The failure is based on the Serviceability index (PSI). The PSI is related to the road geometry features IRI and rut depth (RD) as exemplified in the following equation

$$PSI = a_1 \cdot e^{b_1 \cdot IRI} + a_2 RD^2 + a_3 \sqrt{C + S + P} \qquad (8)$$

where C is the total cracked pavement area, S is the total pavement disintegrated area (pot-holes and ravelling), P is the pavement patching area, and a and b are experimental constants. The remaining life (RL) can then be calculated based on the total ESAL to date (N_p) and total ESAL to failure ($N_{1.5}$), where 1.5 denotes the PSI threshold, as in

$$RL(\%) = 100(1 - \frac{N_p}{N_{1.5}}) \qquad (9)$$

Several other physics-based models were developed, even including some empirical basis as mentioned before. Regarding parametric models (by opposition of the global models such as AASHTO one where the pavement condition in given by a single index), the HDM-4 models (Highway Design and Maintenance Model) are good examples. Those are deterministic pavement performance models based on regression analysis but structured based on the mechanistic-empirical concepts of pavement deterioration, and have been used by various road agencies all over the world for the last decades.

5.2 Data-driven models

The choice of data driven models for condition prediction and maintenance planning of linear infrastructure asset is based on the monitoring technology, technique and strategy. These three aspects of condition monitoring can be further implemented for digitalization, processing, diagnostics and prognosis. For prognosis, state description of the asset and the frequency of inspection and condition monitoring campaigns are important factors to consider for reliable and efficient model and algorithm development.

5.2.1 Nowcasting

From infrastructure management viewpoint, there are several inspection methods and systems that can be used for nowcasting, i.e. assessing the current condition of the assets. The diagnosis carried out to obtain the asset condition is a complex job that involves in-depth analysis of the system and often involves experts performing inspections and analyzing features about established thresholds. For linear assets, such as road and railway, nowcasting is still a highly manual procedure. Examples of inspections used for nowcasting is presented in

Table 10.

TABLE 10: NOWCASTING ON LINEAR ASSETS USING EXPERT ASSESSMENT DURING INSPECTIONS

Infrastructure/ asset	Feature	Method/Inspection	Output
Road pavement	Surface defects and structural conditions, e.g. cracking	Visual inspections (or automatic assessment based on image processing)	● Proportion of defects and cracks within a certain area. ● Estimated cracking rate (%) and surface defects rate (%) ● Severity level of defect
Railway track	Rail profile, gauge, surface defects (RCF, head checks, squats etc.) and corrugations	Ocular inspections, contact based measurement systems and optical systems	Severity level of defects [no. or no./km]
Railway switches and crossings	Switch blade position	Continuous monitoring using sensors	Malfunctions per switch type over a short time horizon [no. or %]

In addition to the existing expert-based assessment for nowcasting, there are other unsupervised and semi-supervised methods that can be used when measurement vehicles are employed for collecting large volume of data. These methods can be based on residual analysis where the deviation of a measured signal from a reference signal representing a healthy condition is analyzed, e.g. utilizing physics-based models.

Other techniques are symbolic models (fuzzy logic), multivariate statistical analysis, machine learning, and artificial neural networks. The usage of these techniques depends on high amount of relevant data for both healthy and unhealthy conditions. Features derived from inspections and condition monitoring data are combined with asset information (e.g. type and age of various asset types), operational data (e.g. number of axles, and line speed), maintenance data (e.g. number of repairs, repair level), and contextual data, (e.g. weather, location of asset). These data, further, can be used for Alert management:

1. Through objective value of the explanatory features obtained with measurements:
    a. Values of the considered features (F_i) together with their thresholds.
2. By means of subjective values that identify the severity of the asset condition referred to a healthy condition:
    a. Subjective evaluations associated to any individual feature (A_i).
    b. Subjective evaluations associated to a combination of features (C_i).
    c. A global subjective evaluation associated to the condition of the asset (G).
    d. An overall assessment regarding Requirement for maintenance (Yes/No).

All these data have not been available at the same time. This mean that if the Maintenance Manager is interested only in a global evaluation (G), the subjective evaluation for individual features (A_i) and subjective evaluations associated to a combination of features (C_i) are not needed. Examples of features, methods of inspection, and outputs of infrastructure are shown in

Table 10.

Besides acting as a direct input for alert management, the asset condition resulting from nowcasting will allow the computation of several indicators, to be used for:

- Acting as the current condition when defining performance goals or minimum levels to assure while running optimization models to support decision-making;
- To provide additional data to the Maintenance Manager to confirm or support any subjective evaluation or conclusion made from a specific field observation;

As illustrated in Figure 1, the linear asset modelling can be categorized either as microscopic or macroscopic. Microscopic refers to segment analysis whereas macroscopic refers to multi-segment or network analysis. The latter modelling hierarchy is used to for maintenance planning and to support the Infrastructure Manager in the definition of future maintenance budgets per the verified trend of the asset condition. The cumulative percentage of a condition indicator is an example of how nowcasting can provide information to support the Infrastructure manager in such decisions. In Figure 24 the cumulative percentage of the rail geometry parameter Longitudinal level for two railway sections (~150 km) is shown. In addition, the percentage of values of the considered indicator within ranges related intervention limits can be presented as shown in Table 11 for one of the track sections.

TABLE 11: NOWCASTING TRACK GEOMETRY USING THRESHOLDS.

	DL	ML	AL	IL1	IL2	IAL	
Thresholds	<0.75	<1.00	<1.80	<2.50	<2.90	<3.20	>3.20
Percentage	20.9%	30.2%	43.3%	5.0%	0.5%	0.0%	0.2%
Cumulative percentage	20.9%	51.0%	94.4%	99.4%	99.8%	99.8%	100%
DL: Design level, ML: Maintained/New adjusted level, AL: Alert limit, IL1: Intervention limit 'low', IL2: Intervention limit 'high', and IAL: Immediate action limit							

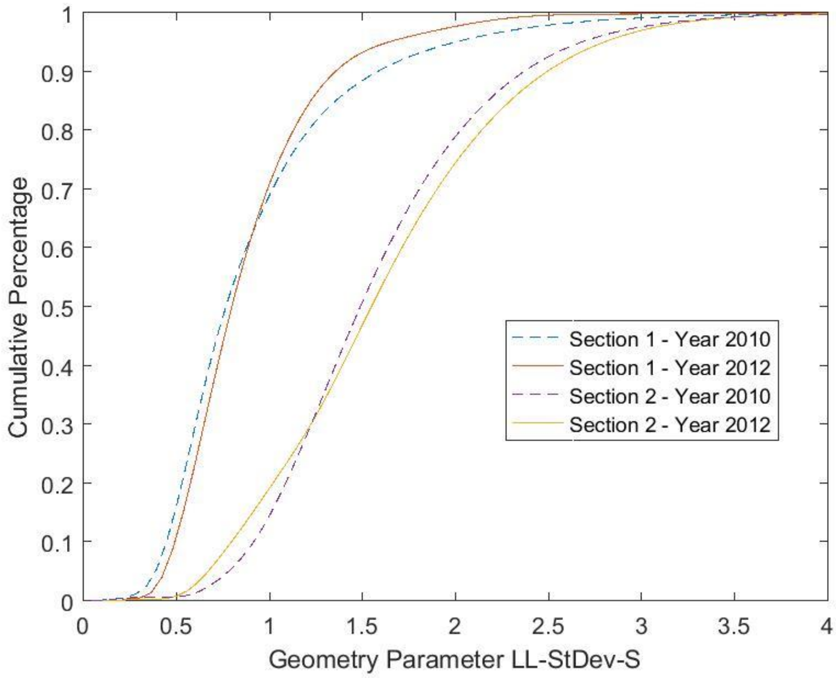

FIGURE 24: NOWCASTING TRACK GEOMETRY USING CUMULATIVE PERCENTAGE.

5.2.2 Forecasting

The deviations of the geometrical condition indicators from the mean or designed geometrical characteristics are often used for maintenance prediction and planning. Furthermore, these geometrical parameters can be aggregated to a quality index for benchmarking, monitoring maintenance and renewal and strategic decision making and for both road and railway infrastructure. The output of a forecasting model should contain two components: (i) an estimated time to failure, also referred to as remaining life or remaining useful life, and (ii) an associated confidence limit.

For alert management (see Figure 22), it is not just in the actual state condition of any asset of the transport infrastructure that is of interest but also in the forecasted state conditions of further temporal scenarios. Focusing on a particular asset-segment, *a-i th*, the current and the estimated evolving conditions will be taken as features themselves, defined by$X_p|_{a-i}$, and may be referred to one or several other independent features of the assets, denoted by $X_j|_{a-i}$ where subscript *j* stands for the *j-th* feature. The assessed condition $X_p|_{a-i}$ can be either a design parameter, a feature monitored by (periodic or random) launched inspections and auscultations, or a new feature created for this purpose. In both cases these asset condition features will constitute new records to be stored as new features in the system database, in order to be retrieved when needed. Figure 25 depicts the estimated asset condition $X_p|_{a-i}$, function of the independent variable X_t(e.g. time), showing a sample of three values corresponding to the evolution of the feature, in future scenarios; the most probable value is identified by the bold broken line in the middle of two extreme border lines corresponding to lower/higher probabilities per some statistical reliability (e.g. 0.955, 0.783). The vertical cross-section lines stand for the values of the independent variable $X_{tm+1}, X_{tm+2}, X_{tm+3}$ at three future scenarios; the nowcast scenario X_{tm} is pinpointed by the square dot. The horizontal thresholds shown define the Normal Limit (L_N) and Exceptional Limit (L_E), denoted by RT_i and RT_{i+1} respectively, of the asset condition criteria set by the relevant standard on design parameters. Other thresholds affecting the track geometry quality can also be considered, as it is the case of the Alert Limit (AL), Intervention Limit (IL) and the Immediate Action Limit (IAL) indicators. Per the criteria defined by the applicable standards (e.g. European Standard, EU Member State Standard, Rail Administration Standard), the asset condition will be quantified according to the proximity the forecasted values show respect to the specified limits. Besides, the previous cited probabilities of the estimated condition values are also a very valuable piece of information to assess the severity of each scenario.

As it can be seen in the Figure 25, the forecasting scenario of the asset condition will be characterized by the value of all explicative features and their associated uncertainties. Then, there are different ways to quantify the features in each scenario; by a probability distribution, by a value (mean) and a standard deviation, by a confidence interval, and by using non-probabilistic theories and tools such as possibility and fuzzy approaches.

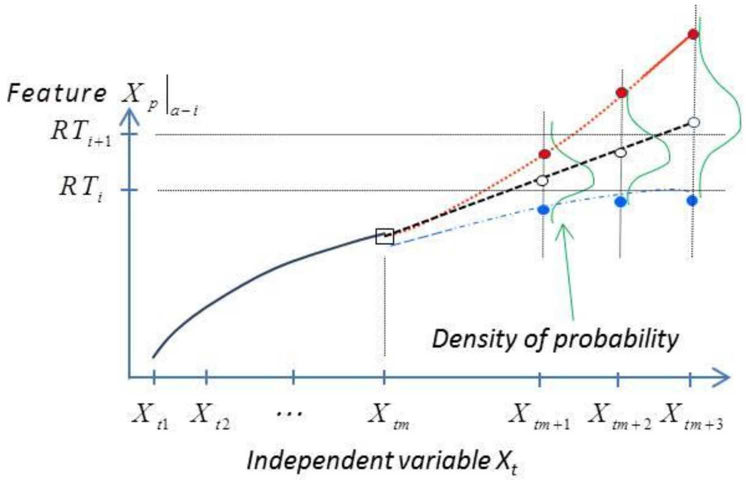

FIGURE 25: ASSET CONDITION PREDICTION

There are different types of prognostics as per the principle of modelling as shown in Figure 26 (Si et al., 2011 and Sikorska et al., 2011). Life expectancy and Machine learning are both data-driven approaches that rely on monitored and historical data that are used to learn the systems behavior (Sutharssan et al., 2015). Two categories of Life expectancy models are statistical models (e.g. Regression and Autoregressive models) and stochastic models (e.g. Reliability and Covariate based hazard models and Bayesian methods). A summary of the data-driven methods and its advantages and disadvantages is shown in

Table 12.

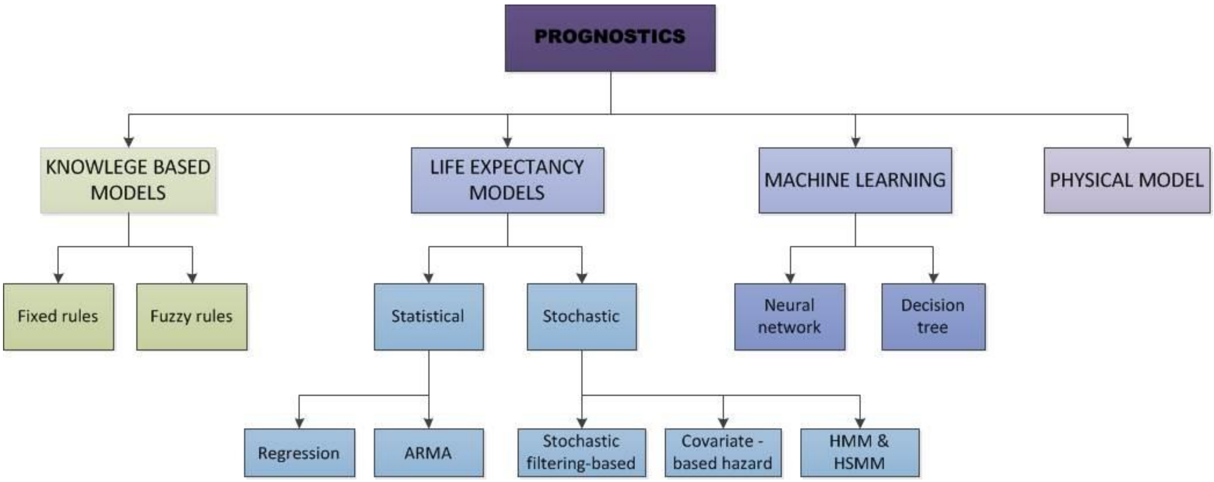

FIGURE 26: DIFFERENT METHODS OF PROGNOSTICS

TABLE 12: DATA-DRIVEN METHODS FOR PROGNOSTIC MODELLING OF LINEAR ASSETS

Method	Advantages	Disadvantages	Input from	Output
Regression-based	Due to the availability of data, forecasting can be updated, checked and validated for multiple variables.	There is no understanding of the physical system	Condition data	Performance parameters (as defined) and error measures
Reliability	Simple and works well with time to failure data	The is no information about the condition. Can be complex with multi-state system or for continuous degradation modelling.	Failure data	Survival function, Mean Time to Failure (MTTF).
Markov models	Well establish approach that can model several failure mode scenarios.	Can only model previously known faults. Assumes a single monotonic failure degradation. Large volume of data required for training.	Statistically correlated data of node states (or expert knowledge) Prior distribution of parameters	Probabilities of next conditions
Stochastic filtering	Can be used with incomplete and noisy measurements and to model multivariate and dynamic deterioration process.	Can diverge easily. Can be computational intensive for non-linear systems. Result sensitive to prior knowledge and selection of prior distribution. Modelling experts needed.	Condition monitoring data. Degradation model (prior knowledge) Prior distribution of parameters	Probability density function of future states.
Covariate hazard	PHM with time-dependent covariates over the other statistical approaches is that covariate information can be easily combined with a baseline hazard function. Thus, the effect of different covariates on the total hazard can be easily evaluated.	(1) The models mixed the casual relationship of different covariates. (2) When the evolution of covariates is stochastic, another process (mostly a Markov chain) must be used for describing the covariate process. (3) Strict (albeit implied) assumptions regarding nature of underlying process	Event time, Covariate parameter,	Reliability estimation, RUL estimation, nowcasting and forecasting in this project

Hidden Markov models	The failure degradation does not need to be monotonic.	Can only model previously known faults. Can be computationally intensive for many hidden states.	Node state training data (condition data)	Probabilities of future conditions
Machine learning	Can handle data with high volume, velocity, variety and complexities. Categorical data can be used as predictor. It is efficient for continuous state modelling.	In some instances, estimation of prediction interval can be complex or impossible. The model performance can be very poor with few data.	Condition data, operation data (traffic volume, axle load, traffic type etc.), environmental data, maintenance data.	Present health status, classes of future states and future condition at specific time.

5.2.2.1 Statistical Methods

These methods study the trends in historical data and utilize mathematical methods to forecast the future. The assumption underlying in the technique is that the trends and behavior of the past is in cohesion with the future. These models assume that the deterioration is a continuous process and threshold values are used to distinguish assets with different conditions using condition asset variables through monitoring, trending and prediction by predefined thresholds (Thaduri, et al., 2013). Several mathematical models were defined in the literature such as weighted smoothing, decomposition, turning point analysis, auto regressive models, linear regression, etc. to assess the condition of the assets. The commonly used methods are regression methods that are frequently used for lifetime estimation (Meeker and Escobar, 1998). Jardine et al. (2006) have given a detailed review on several regression methods that can be useful for remaining useful life estimation.

There are few studies that utilize the regression based models in linear assets (Luff, 2012). Davies et al. investigated the multiple factors such as length, size, location, material, etc., affecting condition of a sewer in London using logistic regression (Davies, et. al 2001). Ariaratnam et al. studied sewer pipes from Edmonton, Canada and found that age, diameter and waste type were significant variables by predicting the probability of a sewer system (Ariaratnam, et.al 2001). Sun et al, 2011 proposed multiple failure characteristics with mixed failure distributions of linear assets using hazard predictive method (Sun et al., 2011). Ting (2012) predicted the likelihood of failure of underground linear assets using the survival analysis (Ting, 2012). Other works in linear assets are for distributed pipeline assets (Li et al, 2011), electricity transmission (Li et al., 2016), civil infrastructure (Falls, et.al 2005), rail breaks (Söderholm and Bergquist 2016) and geometry degradation (Famurewa et al, 2013).

5.2.2.2 Reliability models

Based on statistical models and reliability data (for instance, Time to Failure and time to repair) the probability of failure with respect to time e.g. Mean Time to Failure, can be provided. Reliability analysis of repairable units can be classified into parametric and non-parametric methods. Among the parametric methods, stochastic point processes, e.g. the homogeneous Poisson process (HPP), renewal process (RP), trend renewal process (TRP), branching Poisson process (BPP), and non-homogeneous Poisson process (NHPP) can be used for data analysis.

When the failed unit is replaced or restored to an as good as new condition then usually time between failures of repairable unit are independent and identically distributed. In such cases, homogenous Poisson process and Renewal process are common model to analyze the reliability of a system. From the probability density function the Remaining life can be calculated as the time remaining before a certain failure are expected to occur by conditional reliability function (R) as:

$$MRL(t) = \int_0^{\infty} R(x|t)dx = \frac{\int_t^{\infty} R(x)dx}{R(x)} \quad 10$$

Various distributions can be used to model failure data, including the Exponential, Normal, Lognormal, and Weibull functions. In reliability engineering the Weibull Distribution function is perform well due to its ability to describe many different types of failure mode and related. Furthermore, in case of having deterioration, Weibull process is one of successful model to estimate the reliability of the item and consequently remaining useful life of the asset (Garmabaki et al., 2016).

5.2.2.3 Markov models

Markov and semi-Markov models are variants of Dynamic Bayesian networks. In Bayesian networks the arcs flow forward in time as for modelling of time series data. The underlying assumption is that future degradation state only depends on the current degradation state. In addition, the states can be revealed directly from condition data (Si et al., 2011). Markov models can have finite number of discrete or continuous, where the latter is often referred to as a Markov process. Semi-Markov models differ from Markov models by not being constrained to constant failure rate. Kharoufeh et al. (2010) developed technique to combine environmental data with stochastic failure models to assess the current or future health of the system. Carlin & Chib (1995) used Monte Carlo techniques with Markov models for the forecasting and remaining life estimation. Morant et al. (2016) presented a framework using Markov models for the safety and availability of the railway operation, and the probability of the signaling system not to supervise the railway traffic.

While Hidden Markov models, Semi-Markov models and Petri nets would include in the evaluation the failures on redundant systems or components, and the ageing of the system, this would require having further assumptions since some of the information needed is not possible to obtain. Hidden Markov models are extension of Markov models where not all states are directly observable, i.e. this overcome the disadvantage that the states only can be revealed directly from condition data. The transition information of hidden states is obtained from training the model with degradation data. Hidden Markov model is computationally heavy but allow for modelling of time series data without specific physical understanding.

5.2.2.4 Stochastic filtering

Stochastic filtering is a common approach for implementing Bayesian network models, such as Kalman and Particle filtering. The Kalman filters estimate the underlying state of a dynamic system (posterior PDF) by extrapolating from prior state and noisy measurements. Kalman filtering technique has been used for a long time in health monitoring, see e.g. Sarma et al. (1978). Using a state space model both unobserved and observed condition monitoring data can be used to model the conditional remaining life. Kalman filtering assumes that the system model is linear and that the residual is Gaussian; therefore, several modifications and alternatives have been explored, one being

the Monte Carlo-based particle filter. Good comparison between particle filter and statistical learning algorithms (multiple regression and neural network) has been provided by Saha et al. (2009). The PDF of the RUL can either be in closed form or estimated from numerical simulation techniques. In the literature, the application of Kalman and Particle filters for the purposes of remaining life estimation are found for engineering assets such as rotating machinery and crack development.

5.2.2.5 Covariate hazard based

In real case situations, the degradation process is caused by one or more factors that are called covariates. For example, wear-out process of rail component can be affected by temperature, material properties, axle load and running speed and these are covariates.

Proportional hazards model (PHM) is one of the most reported covariate-based models for prognostics. PHM is applied in different application due to its generality, flexibility, and simplicity (Cox, 1972). Thus, PHMs have been widely used to relate the system's condition monitoring variables and external factors to the failure of a system and hence have been applied in different areas of life data analysis, nowcasting and forecasting.

RUL estimation by Proportional hazards model (PHM)

The RUL of an asset is a random variable and it depends on the current age of the asset, condition monitoring data, the operational environment. Consider a nonnegative random variable T which represents random time to failure of an asset. Let $R(t) = P(T > t)$, where $t \geq 0$ and $R(t) > 0\ \forall t$, be the related reliability function. Let T be continuous so that its density function *f(t)*, and its hazard function *h(t)* exist. Then assume that $X_t = T - t$ is the remaining life (RL) of T at time t. The mean remaining life (MRL) function is defined in Eq. (11) as the expected value of the RL times after a fixed time point t.

$$\mathrm{MRL(t)} = \mu(\mathrm{t}) = \mathrm{E(T - t|T > t)} = \frac{\int_{\mathrm{t}}^{\infty} \mathrm{R(x)dx}}{\mathrm{R(t)}} \tag{11}$$

It is clear that $\mu(0) = \mu = MTTF$, where MTTF is the mean time to failure. Hence, the Eq. (11) can be interpreted as

$$\mathrm{MRL(t)} = \mu(\mathrm{t}) = \frac{\mu}{\mathrm{R(t)}} - \mathrm{t} \tag{12}$$

For more details see Hoyland & Rausand (2004) and Garmabaki et al. (2016).

In addition, let $Z(t) = [Z_1(t), Z_2(t), \dots, Z_n(t)]$ be all covariate factor vector function, i.e. a vector consists of n degradation feature at given time t. The effect of the covariate on the RL can be defined as $X_t = E\big(T - t|T > t, Z(t)\big)$. Hence the probability density distribution of the RUL can be given as

$$\mathrm{f_{x_t}(x_t|Z(t))} = \frac{\mathrm{f(t+x_t|Z(t))}}{\mathrm{R(t|Z(t))}} \tag{13}$$

where $R(t|Z(t)) = P(T > t|Z(t)) = e^{\left(-\int_0^t \lambda(x|Z(x))dx\right)}$. The hazard rate of PHM can be expressed as the hazard function $\lambda(t|Z(t)) = \lambda_0(t)e^{(\beta' Z(t))}$, which consists of a baseline hazard function $\lambda_0(t)$ and exponential covariate function $e^{(\beta' Z(t))}$. For estimation of baseline function $\lambda_0(t)$, it is important to collect failure data.

5.2.2.6 Machine learning

An important aspect of condition monitoring of linear asset is to predict the evolution path or future state of systems or constituent components for a projected operational context using a prognostic model and appropriate algorithm. Condition prognostic of linear asset is increasingly becoming difficult using conventional physical and regression models due to some reasons. These include: complex design and integration, spatial extension, heterogeneous engineering, operational profile and maintenance program and environmental. The vast quantity of condition monitoring systems and data requires an advanced condition prognostic approach that is more robust, effective and reliable. A useful method that is promising for linear asset condition modelling is machine learning. Machine learning makes use of computers to learn pattern in data and project into future without being explicitly programmed. In condition forecast of linear asset, this method can be used to devise complex models and algorithms to uncover hidden insights through learning from historical relationships and trends in the data analysts to produce reliable, repeatable foresights and results.

There is a large library of machine learning algorithms for regression, classification, clustering, and anomaly detection. Each is designed to address a different type of machine learning problem. Basically, the input into machine learning algorithm depends on the type of algorithm. In general, the input are relevant features (e.g. IRI for roads, geometry parameters for rail, weather traffic, maintenance actions) that indicates the health of the asset, usage, actions and external condition of the asset. The output can be one of the following: Estimates of future health grade, Prediction of faults and failures with associated likelihood probability, Estimate of RUL or time to next maintenance. Examples of relevant algorithm for linear asset condition prognosis and their unique property are given in the figure below.

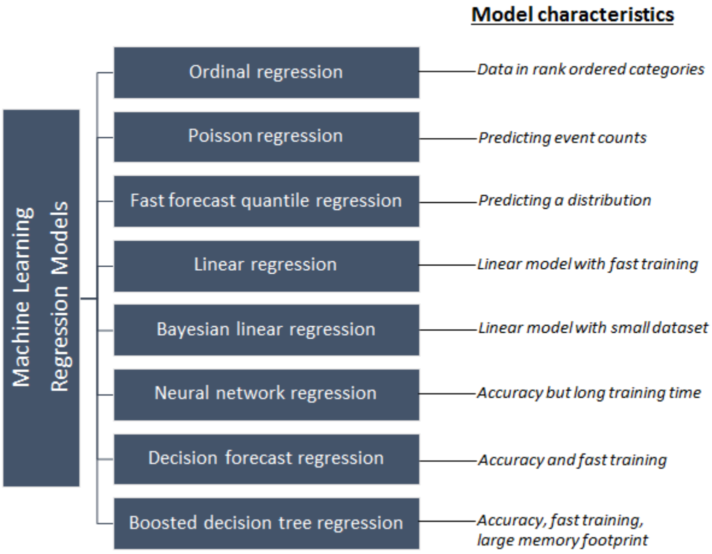

FIGURE 27: MACHINE LEARNING ALGORITHMS WITH THEIR ADVANTAGES FOR SELECTION PURPOSE (ROHRER, 2016)

5.3 SYMBOLIC MODELS

DEARTH OF DATA IS THE GREATEST ACKNOWLEDGED OBSTACLE TO THE DETERIORATION AND RECOVERY MODELING OF THE LINEAR INFRASTRUCTURE THE LINEAR INFRASTRUCTURE ASSETS. IN SUCH CASES, SYMBOLIC MODELS CAN BE INTERPRETED AS KNOWLEDGE-BASED SYSTEM AND MODELED BY BASED SYSTEM AND MODELED BY FUZZY RULE-BASED SYSTEM. RULES ARE FORMULATED AS PRECISE IF-THEN STATEMENTS; THESE ARE OFTEN BASED

STATEMENTS; THESE ARE OFTEN BASED ON HEURISTIC FACTS ACQUIRED BY ONE OR MORE EXPERTS OVER SEVERAL YEARS (BIAGETTI & SCIUBBA, 2004). YEARS (BIAGETTI & SCIUBBA, 2004). THE USE OF FUZZY RULE BASED SYSTEM AND FUZZY TECHNIQUES HELP TO INCORPORATE THE INHERENT INCORPORATE THE INHERENT IMPRECISION AND SUBJECTIVITY OF THE DATA, AS WELL AS TO PROPAGATE THESE ATTRIBUTES THROUGHOUT THE MODEL, ATTRIBUTES THROUGHOUT THE MODEL, YIELDING MORE REALISTIC RESULTS. FUZZY EXPERT SYSTEMS ARE SUMMARIZED IN

SUMMARIZED IN

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TABLE 13: SYMBOLIC METHODS FOR PROGNOSTIC MODELLING OF LINEAR ASSETS

Method	Advantages	Disadvantages	Input	Output
Fuzzy Expert Systems	Simple to develop; easy to understand, flexible, - and are often robust, in the sense that they are not very sensitive to changing environments and erroneous or forgotten rules.	Not accurate, ie. it provides approximate output data; lack of exact mathematically description; domain experts required to develop rules.	Maintenance knowledge; Maintenance experience; quality before maintenance; quality after maintenance; Training; environmental condition, etc.	Output is a number within [0,1] which can be used solely or combined with closed form recovery model proposed in the literature.

Symbolic model uses empirical relationships described by linguistic variable. Symbolic model is not relay on statistical or mathematical relationships. For example, a linguistic variable for the quality of maintenance task can be categorized as high repair quality, moderate repair quality and low repair quality. The process of symbolic model begins by collecting as much initial system information as possible. In addition, work orders and maintenance reports, handwritten by maintenance crews and interviews can be used. Maintenance crews can provide valuable verbal information; however, this information needs to be processed before further investigation. Fuzzy Inference Systems given in Figure 28 can be used in such cases to capture the relation between linguistic variable and related rules. Fuzzy inference systems (FIS), especially the Mamdani and Sugeno type model, can be efficiently used as a bridge between the symbolic model and a recovery and forecasting model (Kothamasu & Huang, 2007). Recovery level estimation after maintenance of rail and road can be viewed as an application of symbolic model. The method for defuzzified output for effectiveness of maintenance task can be shown in Figure 28. Figure 29 depicts the method for identifying maintenance intervention.

Consider a domain described by a function $y = f(x1, x2)$, a *Mamdani* type FIS in this domain would consists of rules of the form "IF *x*1=*"Maintenance quality"* is low AND *x*2= *"environment*'s *condition*" is harsh THEN *y="quality after maintenance"* is low,'' where low, medium, harsh and high are linguistic terms with functional forms like Gaussian, Sigmoid, etc., also known as membership functions.

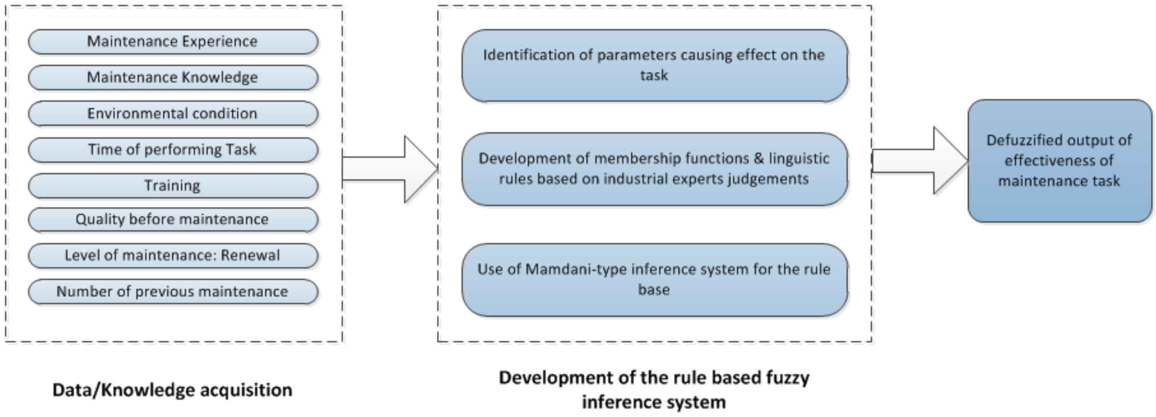

FIGURE 28: SYMBOLIC METHOD FOR MAINTENANCE INTERVENTION

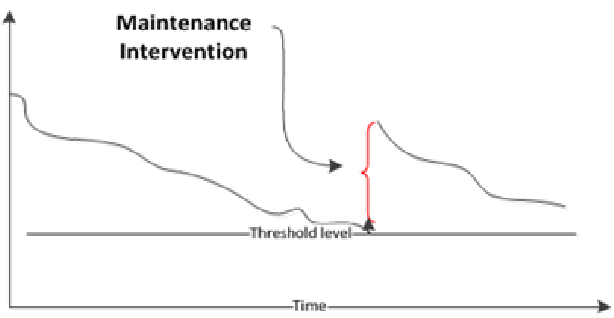

FIGURE 29: IDENTIFYING THE MAINTENANCE INTERVENTION

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