POLITECNICO DI TORINO

Corso di Laurea Magistrale in
INGEGNERIA GESTIONALE (ENGINEERING AND MANAGEMENT)

Master of Science (MSc) Degree
Thesis

Predictive analysis of defective wheel-rail interaction for optimization of railway track maintenance and safety

Supervisors

Prof. Franco Lombardi

Prof. Giulia Bruno

Candidate

Louis Kituyi Lissandro

July 2021

(This page intentionally left blank)

To my lovely little daughter Pauline, you who has inspired me to overcome obstacles and conclude this thesis. They say a 3-D perspective is better than a 2-D perspective, I couldn't agree more. Just when I felt overwhelmed trying to manage my 2-D responsibilities (full-time work and studies) you came to my life a year ago and added another dimension to it, now 3-D (full-time work, studies and father). While this didn't ease up things, it provided me with immense joy that consequently generated the drive in me to get back on track with my studies and here we are, a master's degree in Engineering and Management for papa. We both know the true management course that awaits me is that of being a good father and always being there for you. That has no study period, no limit nor a degree, but it is what I'll pursue and be committed to for the rest of my days.

Acknowledgement

I wish to acknowledge the contribution of the following people to the successful completion of this thesis:

- My supervisors, both Professor Franco Lombardi and Professor Giulia Bruno for accepting and providing constant support and guidance throughout this project. Immense gratitude also goes to Research assistant Mr. Emiliano Traini for his professionalism and valuable advice regarding the research matter.

- Eng. Cesare Santanera (CEO of DMA Srl and my employer) for his valuable time, fruitful discussions and most importantly granting me a comfortable atmosphere for research and access to material and other resources within the DMA walls that was key to the accomplishment of this thesis work.

- Eng Angelo Zingarelli (DMA Srl) and Eng. Alberto Magnani (DMA Srl) for their technical expertise and for sharing their knowledge on railway systems which was indispensable for bridging theoretic concepts to the real-world railway applications. Gratitude is also extended to my other colleagues in DMA who in one way or another have instilled railway related knowledge in me over the years.

- Finally, to my family and friends for their immense support and continuous encouragement throughout this research work. Profound gratitude to my fiancée for her love, patience, and for always standing by me in difficult times. This accomplishment would not have been possible without her.

Abstract

Increase in railway demand has significantly been met by rail operators through technological advances that have seen increase in train speed and axle loads, both to which have ensured an increase in operating capacity. However, from the infrastructure side, this has led to an increase in rail traffic demand that has been met with little extensions of rail infrastructure.

Infrastructure managers (IMs) are faced with the challenge of having to increase the number of runs passenger and freight trains make across a relatively fixed network. This growing pressure on increasing operation time also reduces the infrastructure accessible time for maintenance activities. Furthermore, the traffic on railway lines varies from vehicle type, load, and speed which subjects the track to a wide range of stresses. These stresses and generally effects of rail vehicle performance on the infrastructure need to be monitored and managed effectively to avoid operational downtime and delays, increased maintenance and in the worst-case scenario derailment.

Therefore, there is need for infrastructure managers (IMs) to adopt innovative and sustainable operation and maintenance strategies to be able to meet these challenges. With improved understanding of rail vehicle running behaviour on the track from the wheel–rail interface perspective, infrastructure managers (IMs) can be better placed to formulate suitable cost-effective asset management and maintenance strategies.

In this thesis focus is placed on the wheel–rail interface. Defective wheelset lateral movement on the rails (truck hunting) is addressed. Potential safety and maintenance issues i.e., derailment and rolling contact (RCF) defects respectively that may arise due to excessive bogie/truck hunting are also addressed. The study aims to facilitate improvements and optimization of maintenance decision-making for railway infrastructure.

Keywords: railway track, wheel–rail interface, vehicle dynamics, maintenance, optimization, derailment, truck hunting, rolling contact fatigue (RCF) defects, infrastructure management.

(This page intentionally left blank)

List of Symbols

y	movements of the wheelset on the track in y direction
λ	wavelength
e	distance between contact points (approximately 1500 mm for standard railway gauge)
α or ψ	wheelset angle of attack (AOA)
tan γe	equivalent conicity
tan γ	contact angle
v	speed of forward movement of the railway vehicle
Δr	difference of the roll-radii between right and left wheel
r0	radius of the wheels when the wheelset is centred on the track
r1	roll-radius of the right wheel
r2	roll-radius of the left wheel
a	semi-wheelbase
Cx	longitudinal stiffness of rail vehicle primary suspension
Cy	lateral stiffness of rail vehicle primary suspension
m	mass of bogie
I	yaw moment of inertia of bogie
μ	friction coefficient
G	track Gauge
Wa	wheelset hunting motion amplitude
Wm	wheelset average lateral displacement
σ	standard deviation

List of Abbreviations & Acronyms

AOA	Angle of Attack
B-to-B	Back-to-Back wheel gauge
CBM	Condition-Based Maintenance
CWR	Continuous Welded Rail
DNV	Det Norske Veritas
EC	European Commission
ECM	Entities in Charge of Maintenance
EU	European Union
FMECA	Failure Mode Effects and Criticality Analysis
FRA	Federal Railway Administration
GCC	Gauge corner cracking
IM	Infrastructure Manager
LCC	life cycle cost
L/V	Lateral force to Vertical force ratio
NDT	Non-Destructing Testing
ORE	Office for Research and Experiments
RAMS	Reliability, Availability, Maintainability and Safety
RCF	Rolling Contact Fatigue
RCM	Reliability Centered Maintenance
ROI	return on investment
RPMS	Rail Profile Measurement System
RU	Railway Undertaking
THM	Truck Hunting Measurement system
UIC	Union International des Chemins de Fer
WPMS	Wheel Profile Measurement System

List of Figures

List of Tables

List of Equations

Content

PART I

State of the art research – wheel-rail interface phenomena influence on vehicle stability and implications on maintenance and safety.

1. Introduction

1.1. Background

Railway is a prime mode of transportation in many countries, proving to be the transport backbone of a sustainable economy and a vital service to global society. With the advancement of technology, the changing environment and increasing customer demands, railways are having to upgrade their various operational activities constantly [52]. To this extent, railways around the world are in continuous search of solutions to strive for new levels of cost-effectiveness while delivering safe and reliable networks that meet the ever-increasing demand. Moreover, the rail sector is presented with unprecedented opportunities to enhance its attractiveness and boost its competitive edge against other modes of transport thanks to its inherent advantages in terms of environmental performance, land use, energy consumption and safety [47], that provide a sustainable solution to the ongoing pressure placed on all modes of transport to address societal issues such as rising traffic demand, congestion, security of energy and climate change.

Rail transport is the most environmentally friendly form of mass transport, characterized with its low levels of atmospheric emissions compared to automotive and air transport, widespread use of electric traction, low energy consumption due to low friction between rail and wheel and relatively small land use of its infrastructure. [49]. In the 2011 Transport White Paper, the European Commission defined a strategic vision for a competitive and resource-efficient transport system. Part of this vision is aimed at phasing out conventionally fuelled cars from cities by 2050, and a 50% shift in middle distance passenger and longer distance freight journeys from road to other modes such as rail [50] with the aim to achieve a 60% reduction in CO2 emissions and comparable reduction in oil dependency.

To exploit this advantage, the rail sector has seen significant progress through adoption of state-of-the-art technologies to increase operating capacity, especially from the rail undertakings side rather than the rail infrastructure side. New lightweight materials and more efficient construction methods of trains have led to a better track-train interface, and has encouraged increase in train speed, increase of axle load, increase in traction power, and consequently increase in traffic density which has put enormous pressure on existing railway infrastructure and has been met with lesser extensions of rail infrastructure.

Infrastructure Managers (IMs) who are responsible for the design, construction, maintenance, renewal and upgrading of the infrastructure are faced with the challenge of having to increase the number of runs passenger and freight trains make across a relatively fixed network.

The increase in train speeds and axle loads by rail operators has a significant impact on the infrastructure especially when considering rail and track degradation. As traffic on railway lines vary from vehicle type, load and speed, the track is subject to a wide range of stresses. These stresses both static (due to vehicle mass, wheelsets, and cargo) and dynamic (due to dynamic actions like longitudinal acceleration and braking forces, lateral centrifugal forces on curves, rocking of vehicle about 3 axes and vibrational forces induced from imperfections in both wheel and rail surface if not effectively monitored and managed may result in operational downtime and delays, increased maintenance and in worst case scenario potential derailment.

While it is a simpler task to diagnose defects and perform maintenance on rail vehicles it is much more complex to do the same for the hundreds to thousands of kilometers of a railway track in a network. Infrastructure managers (IMs) are persistently faced with maintenance challenges from conducting detailed inspection, planning maintenance schedules, and executing maintenance of sections of the infrastructure that may require intervention. Inevitably, the growing pressure on increasing operation time reduces the infrastructure accessible time for maintenance activities. Furthermore, the ageing of existing infrastructure and the expected growth in passenger and freight volumes as envisaged in Europe (+34% and +40% in 2030 respectively, compared to a 2005 baseline) [47] exerts further pressure on infrastructure managers to strive for maintenance efficiency.

A substantial amount of railway budget is spent on inspection and maintenance of rails. Rail infrastructure accounts for approximately one third of the railway's operating costs. A significant part of these costs is related to labour-intensive maintenance, most of which is preventive, although ad hoc interventions are also needed when faults occur, and this can be particularly costly and disruptive [47]. According to the Office for Research and Experiments (ORE) of the Union International des Chemins de Fer (UIC) track maintenance costs vary directly (60 – 65 per cent) with change in train speed and axle load. [60]. Furthermore, these costs increase if track quality is low. Cannon et al., (2003), in their study estimated that the total cost of annual rail inspection for European Union is around € 375 – 850 million per year [56].

These increasing pressures come with the sector’s expectation of a quick performance improvement to be delivered by infrastructure managers (IMs) as shareholders and governments prefer short payback periods for investments. As a result, IMs are being forced to focus on supplying short term cost and/or performance improvements only [52]. As a capital-intensive industry with long-lasting assets (rolling stock and railway infrastructure), deriving the most value out of the initial investment by reducing costs and extending asset’s lifetime through effective maintenance strategies is of paramount importance to the railways. The long-life spans of railway infrastructure components and their high installation costs mean that decisions have a high degree of irreversibility. In addition, the consequences of low initial quality and insufficient preventive maintenance, i.e., high-cost levels and low system reliability, often only come to light several years later. After reaching certain degradation levels, backlogs in maintenance lead to progressive degradation and, hence, capital destruction.

In recent years, an increasing amount of research on how to improve maintenance and reduce costs in the railway sector has been carried out by various scholars and industry experts. Innovative solutions to enhance infrastructure maintenance strategies and policies to be able to answer to current and future demands have been proposed by different authors. Today the state-of-art solutions that could be deployed involve the adoption of big data, automation and IoT that enable the railways to capture a large amount of data in real-time and quasi real-time from sensors, process and analyse the data in smarter ways in order to better monitor the conditions of railway assets and enhance data-based decision making. In Europe where infrastructure is old and more capacity is demanded, there is vast pressure to shift from reactive maintenance strategies to proactive maintenance strategies such as condition-based maintenance and predictive maintenance as enabled by digital data.

Condition-based maintenance (CBM) is foreseen to be an attractive lever for increasing maintenance efficiency. With efficiency gains of 10 to 15% expected, industry experts estimate that the global maintenance market can save up to approximately EUR 7.5 billion per year by moving towards condition-based maintenance [61]. Condition-based maintenance (CBM) is characterized by application of sensor technology, automation and data analytics that sees diagnostics conducted continuously in real-time or quasi real time as the rail assets – trains and infrastructure are in operation. Failure data collected in the past helps identify a critical parameter threshold where an equipment or component should be scheduled for maintenance to avoid failure. In this way maintenance personnel are presented with an agile approach to work as they know a priori exactly which equipment or component may require intervention, where it is located, which spare parts are required and allocated maintenance window to carry out the intervention.

Predictive maintenance on the other hand requires monitoring of not only the condition of equipment and components themselves but also the condition of factors influencing them. On top of this additional data sources need to be tapped into and managed. Industry experts hold that, the additional jump from a condition-based towards a predictive maintenance scheme would require further effort and additional investment. According to McKinsey study on the rail sector's changing maintenance game (2017), the maximum additional savings on maintenance costs due to the jump towards predictive maintenance is estimated at 10%, not significant enough yet and to be aggressively pursued.

Despite the significant number of recent studies and industry forecasts by sector experts on the potential benefits of an optimized railway infrastructure from a maintenance point of view, there is less emphasis on how IMs can better understand the physical root causes that jeopardize the integrity, efficiency, and safety of their infrastructure in the first place. Many rail deterioration processes are still not well enough understood for infrastructure managers to be able to translate them into unambiguous quantitative relationships between investment and maintenance decisions and long-term quality effects (Ferreira, 1997; Veit, 2003); and uncertainty in these relationships might result in these effects not being sufficiently appreciated [52].

Therefore, it is important for the infrastructure managers to improve their understanding of rail deterioration processes and vehicle running dynamics that contribute to such processes. In this way, IMs can decide a better and cost-effective maintenance solution that could meet budgetary constraints regarding renewal, replacement, inspection frequency and policy development.

Formulating track deterioration models is however not a facile task. A lot of research has been carried out in regard and various models have been developed. Most research has been concentrated on only one or a few mechanisms of track deterioration. This could be taken as a sign of the complexity when modelling track deterioration, and no models include 'everything' (Oberg, 2006).

Kumar et al (2008) in their study of a holistic procedure for rail maintenance, observed a need for an overall track degradation model to develop effective track maintenance procedure and proposed the track degradation model illustrated in Figure 1.

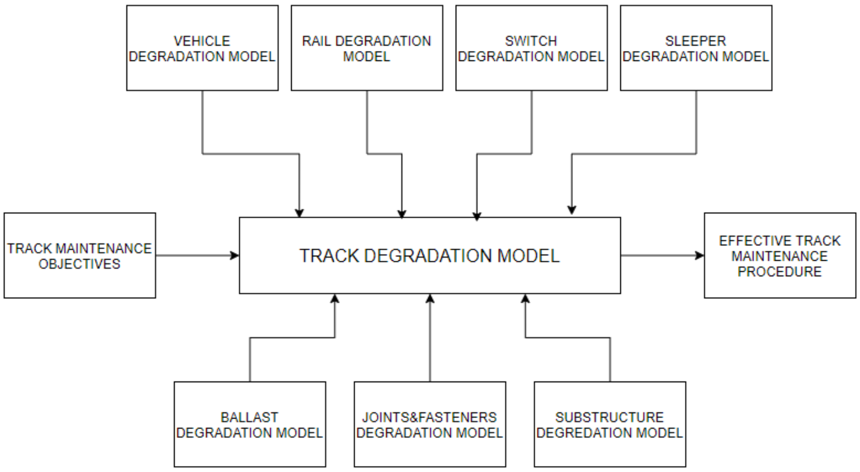


Figure 1: Track degradation model for development of an effective track maintenance regime (adapted from Kumar et al, 2008)

From the infrastructure point of view, it is of further interest to have a good comprehension of vehicle-track interaction and related failures of the track due to poor vehicle performance. Espling et al (2007) categorizes failures due to vehicle and track interaction as depicted in Figure 2.

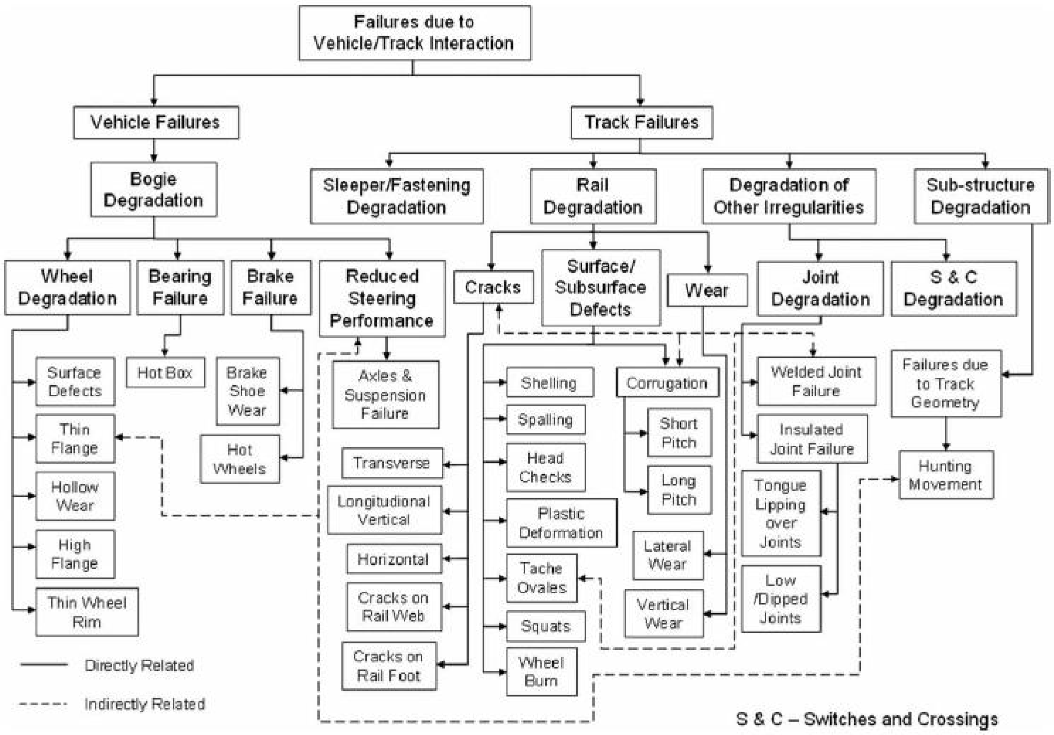


Figure 2: Failures occurring due to vehicle -track interaction (adapted from Sroba and Mass & Espling et al, 2007)

In this thesis the wheel-rail interface is put on the centre stage. The wheel-rail interface involves various core mechanisms including wheelset dynamics, contact mechanics, friction and wheel-rail material which are interlinked, (Figure 3). These mechanisms independently and/or interdependently affect wear, corrugation, RCF defects, mechanical damage, derailment risks, maintenance costs, etc. Therefore, phenomena occurring in the wheel-rail interface affect the vehicle-track system, and vice versa which inevitably implies that the wheel-rail interface has a strong interaction with the total vehicle-track system.

A good management of the wheel-rail interface requires a thorough understanding of the inherent mechanisms and the influence of different parameters. Systems approach to the management of the wheel-rail interface inevitably avoids sub-optimization of the problem.

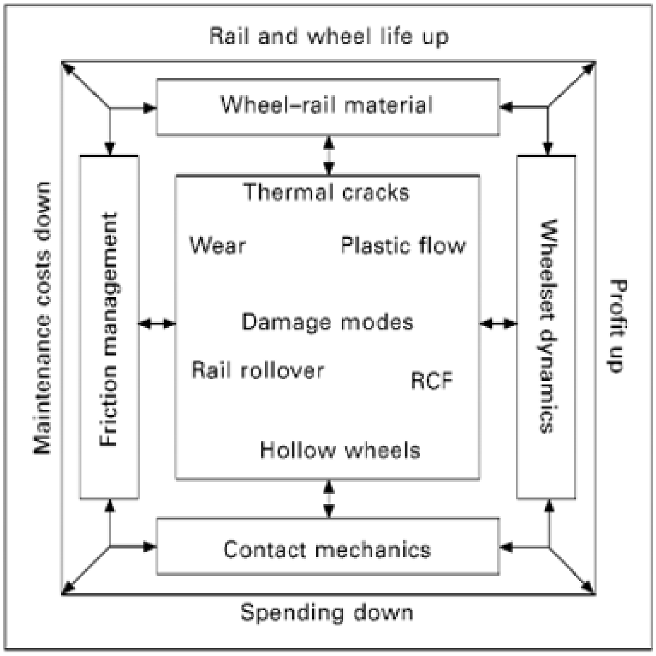


Figure 3: Wheel-rail interface management-systems approach (adapted from Kalousek and Magel, (1997)

The current thesis is confined to concepts of contact mechanics and wheelset dynamics phenomena at the wheel-rail interface. While not explicitly discussed in this study, wheel and rail materials as well as friction management (Figure 3) also play an important role in the optimization of the wheel-rail interface management and are addressed in numerous other studies regarding the wheel-rail interface.

From the contact mechanics perspective, the treatment of wheel-rail contact problem can be divided into two parts: the geometric (kinematic) part, which aims at the detection of the contact points, and an elastic (elasto-plastic) part, which solves the contact problem from a solid mechanics point of view [57]. The output of the geometric part is the essential input for solving the elastic part therefore, therefore it goes without saying that the key to the success of any formulation for the wheel-rail contact problem is the accurate prediction of the contact points location.

For simplicity purposes of this thesis, the study is confined to the first part of the wheel-rail contact problem i.e., the geometric (kinematic) part. Therefore, distribution of stresses and contact patch information that define the elastic part of the wheel-rail interface problem are not addressed. This approach has been taken as the study adopts the infrastructure manager perspective, whose interest is to understand the running behaviour of rail vehicles on their track and most importantly detect defective motion which may harm the track without necessarily understanding the reasons behind that motion that are due to vehicle characteristics. However, it is acknowledged that this second part of the wheel-rail contact problem i.e., elastic part is essential to have a complete understanding of phenomena arising form the wheel-rail interface and for optimization of track maintenance.

In this regard, lateral motion of the rail vehicle wheelset on the track is addressed (hunting). Factors that influence this motion including wheel and rail geometries, rolling radius difference and equivalent conicity are described. The focus is then extended to the case of defective lateral motion of wheelsets (dangerous hunting) that gives rise to vehicle instability and potential risks associated to it in terms of safety and impact on track maintenance in the long run. To this effect, derailment and its repercussions is addressed as worst-case scenario for what concerns the potential safety risks that may be as a result of vehicle instability. For what concerns track maintenance and costs concerns, formation and generation of rolling contact fatigue (RCF) defects on the rails due to defective wheelset motion are addressed. These concepts are developed in the first part of the thesis.

To sum up the research work, the second part focuses on how prediction of phenomena that influence vehicle instability may be performed from an industrial context, thus presenting a real case scenario of an innovative wayside inspection system. The inspection system presented is realized by the company DMA Srl (Turin), a global leader in solutions for railway infrastructure monitoring and diagnostic. The system helps infrastructure managers monitor bogie/truck hunting phenomena that may put at risk the safety of the track and cause deterioration of the rail. Therefore, a feasible technical solution to the problem that is addressed in the study.

1.2. Research problem

Increase in rail traffic demand has been significantly met by rail operators through advances in train speed and axle loads that have ensured the increase in operating capacity. Consequently, this has increased the rail traffic which however has been met with lesser extensions of rail infrastructure by infrastructure managers (IMs). Infrastructure managers are faced with the challenge of having to increase the number of runs passenger and freight trains make across a relatively fixed network. The traffic on railway lines varies from vehicle type, load, and speed, and as a result the infrastructure particularly the track is subject to a wide range of stresses. These stresses if not effectively monitored and managed may result in operational downtime and delays, increased maintenance and in the worst-case scenario derailment.

An enhanced comprehension of rail vehicles running behaviour as observed from the wheel-rail interface and rail deterioration processes originating from the same interface as result of the former is highly valuable to infrastructure managers. Through this understanding, suitable cost-effective asset management and maintenance strategies may be developed not just with a short-term view but with a long-term perspective of bridging the gap from the popular reactive maintenance to a predictive maintenance regime.

1.3. Purpose of the study

The purpose of the current study is to identify and describe defective wheelset movements that are highly potential in jeopardizing rail safety and influencing the development of surface defects on the rail which consequently hinders the maintenance efficiency of the railway track. The study focuses on formulating a solution to facilitate improvements and optimization of maintenance decision-making for the railway track based on an innovative wayside inspection system.

1.4. Research Questions

The main research question in this thesis is the following:

1) How can defective wheel-rail interaction as a result of vehicle's poor running (lateral motion) performance on the track affect the safety and maintenance efficiency of the railway track?

To answer the main question, the subsequent research questions are formulated.

- RQ1: What are the potential risks (maintenance and safety related risks) that arise from defective lateral movement of rail vehicle wheelsets on the rails (dangerous truck hunting)?
- RQ2: What impact do such risks have on track maintenance?
- RQ3: How can defective wheel-rail interaction be predicted?
- RQ4: How can predictive information of defective wheel-rail interaction and related risks be valuable to infrastructure managers for maintenance decision-making purposes?

1.5. Scope and Limitations

The scope of the work is primarily focused on the wheel-rail interface. The study considers maintenance and safety issues as a result of poor vehicle running behaviour (lateral direction only) and from the railway infrastructure perspective. As focus is placed on vehicle stability influenced by kinematic oscillation of wheelsets, this analysis is restricted to tangent (straight) track. Therefore, running behaviour of vehicle wheelsets on a curved track is beyond the scope of this study. Furthermore, since the study is confined to the infrastructure sub-system aspects regarding rolling stock maintenance issues are not considered and neither are ride comfort issues. Other factors that contribute to generation of rail surface defects at the wheel-rail interface such as vehicle suspension design, wheel and rail material properties, and climatic effects are also not considered. While the study is geographically generic in scope, a substantial amount of considerations has been based on the European rail industry which is more complex in nature in terms of structure and standards involved but at the same time provides a significant quantity of available information in regard to the research.

1.6. Structure of Thesis

This thesis is divided into the following chapters:

PART I: State of the art Research

Chapter 1: *Introduction*, introduces the area of research, defines the research problem and formulated research questions, states the purpose, scope, and limitations of the study.

Chapter 2: *The Railway system*, provides an overview of the railway system and its structure. Focus is placed on the infrastructure sub-system and further narrowed down to the track which is the core constituent of the infrastructure and. The track sub system of the railway infrastructure is introduced as the focus of the study.

Chapter 3: *Wheel–rail interface*, literature review regarding the wheel-rail interface from a kinematic point of view is provided. Technical concepts of wheel and rail geometry that are responsible for a good running performance by rail vehicles on the track are addressed. A brief overview of vehicle dynamics is provided with focus placed on the wheelset lateral motion. Parameters that govern the smooth motion of rail vehicle wheelsets on the rails are described.

Chapter 4: *Bogie lateral instability – Hunting problem*, the problem of dangerous lateral movement of rail vehicle wheelset and bogies at high speed is described. Equivalent conicity an important wheel-rail interface parameter that influences bogie stability is addressed.

Chapter 5: *Safety concerns that may arise due to hunting problem- Derailment*, potential safety risks due to unmonitored excessive truck hunting phenomena is addressed.

Chapter 6: *Maintenance concerns that may arise due to hunting problem- Rolling Contact Fatigue (RCF) defects*, potential maintenance risks due to unmonitored excessive truck hunting phenomena is addressed. Economic impact of such defects on the railway sector is also addressed.

Chapter 7: *Track Maintenance*, maintenance management of the track and its challenges are addressed. Current state of the art maintenance approaches are described and the methods of inspection and maintenance deployed to confront the risks of RCF defects and potential derailment are also addressed.

PART II: Industrial Context

Chapter 8: *Necessity of bogie (truck) hunting detection system for railway infrastructure*, this chapter justifies why a truck hunting system is fundamental for prediction of poor vehicle performance in terms of lateral stability that may lead to derailment (most severe concern in railway operation). It provides market data based on European railway industry revealing the importance of such a system but at the same time states its scarce application and the need to be pursued.

Chapter 9: *DMA truck hunting measurement (THM) system*, this chapter provides a real application case of an innovative truck hunting detection system by DMA srl a global leader in solutions for railway infrastructure monitoring and diagnostics based in Turin, Italy. Prediction of dangerous wheelsets and anomalous running performance based on real measurements is presented and briefly analyzed.

Chapter 10: *DMA CONTACT software,* provides insight to a versatile software tool dedicated to wheel-rail contact analysis. Follow up chapter with real applications that backs up the theoretic chapter 3 in PART I.

Chapter 11: *Conclusions* provides the main findings of the study, stating limitations adopted and proposes direction for future work.

2. The Railway System

A system can be defined as a group of interacting or interrelated elements that act according to a set of rules to form a unified whole. A system is described by its boundaries, structure and expressed in its functioning [59]. In the railway context, from a transport functional point of view, the railway system can be seen as composed of the following three constituents – infrastructure, rolling stock and railway operations (Figure 4).

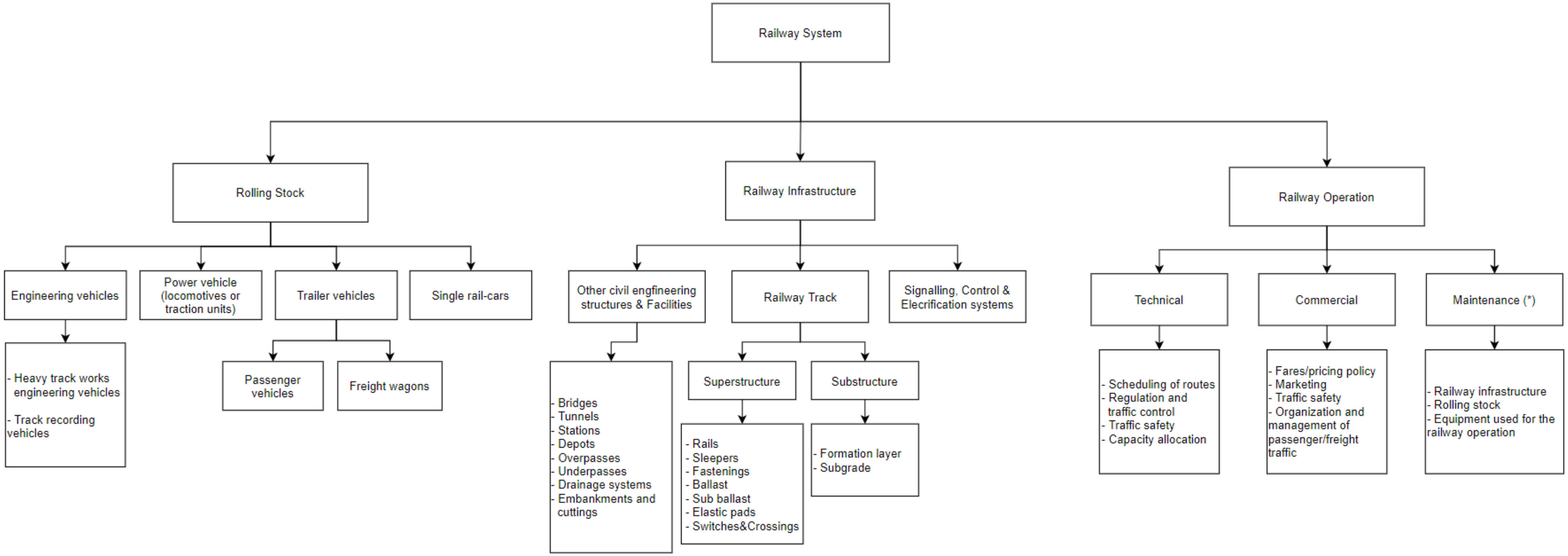


Figure 4: Railway system constituents

(*) – applies to all three constituents of the railway system.

2.1. Railway Infrastructure

Railway infrastructure broadly breaks down to the track and all the civil engineering structures that ensure railway traffic as well as signalling, control and electrification systems, (Figure 5).

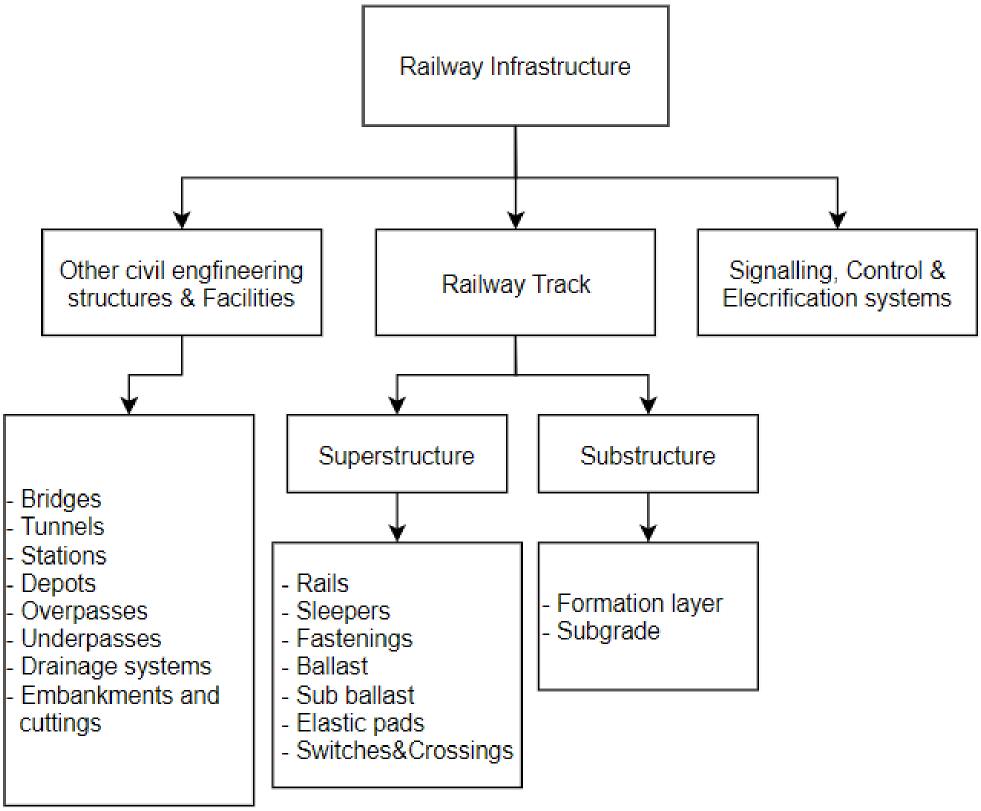


Figure 5: Railway infrastructure sub-system

The scope of this study is based on the wheel-rail interaction and wheelset dynamic performance on the track. Therefore, the focus is confined to the railway track segment. Other civil engineering structures and facilities as well as signalling, control and electrification systems that complete the railway infrastructure sub-system are not addressed.

2.1.1. Railway Track.Structure

The railway track serves as a stable guide for trains with vertical and horizontal alignment (Esveld, 2001). It consists of several components that work together to ensure the correct guidance of a rail vehicle on it. Furthermore, these components that make up the track are of varying stiffness and as a second function they ensure transfer of the static and dynamic traffic loads to the foundation.

In the most common configuration, the railway track consists of rails, sleepers, rail pads, fastenings, ballast, sub-ballast, and subgrade as shown in Figure 6.

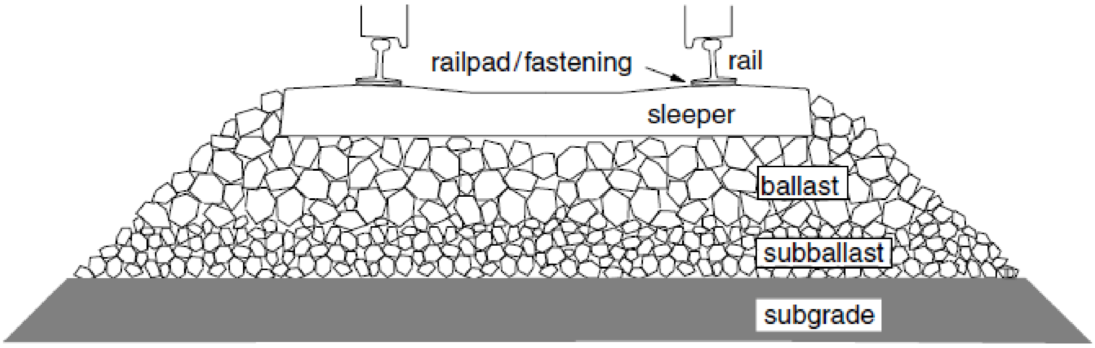


Figure 6: Ballasted track with different components

A further classification of the ballasted track can be made, that is:

i) Superstructure – composition of rails, sleepers, rail pads, fastenings, ballast and sub-ballast.
ii) Substructure – composition of a formation layer and the subgrade.

In non-ballasted tracks which is common for instance in most tunnels, the ballast bed is omitted, and the rails are fastened to concrete slabs resting on the track foundation.

Non-ballasted tracks such as the slab track have gained more popularity in recent times due to increase of train speeds. Ballastless tracks offer a higher consistency in track geometry compared to ballasted tracks.

Figure 7: Non ballasted track – slab track

2.1.1.1. Rails

Rails are the longitudinal steel structures that guide the vehicle wheels evenly on the track. Therefore, it can be stated that the main function of the rails is to provide smooth running surfaces for the train wheels and more importantly guide the wheelsets in the direction of the track. Rails are mounted on the sleepers by means of fastenings and they carry the vertical load of the train and distribute the load over the sleepers. Rails are required to have sufficient stiffness so as to act as beams and transfer the concentrated wheel loads to the spaced sleeper supports without excessive deflection between supports (Ernest and John, 1994). Additionally, rails may also act as electrical conductors for the signaling system.

Rails are manufactured from continuously cast blooms. The most common rail material in Europe is R260 (previously named UIC 900A) which has 0.62-0.82 5% carbon and 0.70-1.20 5% manganese, and a tensile ultimate stress of minimum 880 MPa. Advancement in manufacturing processes have led to significant improvement in rail fatigue performance. There is an increased use of head-hardened rails (R350HT and R35OLHT). Critical parts in switches and crossings are often made from manganese steel (13 % manganese) [5].

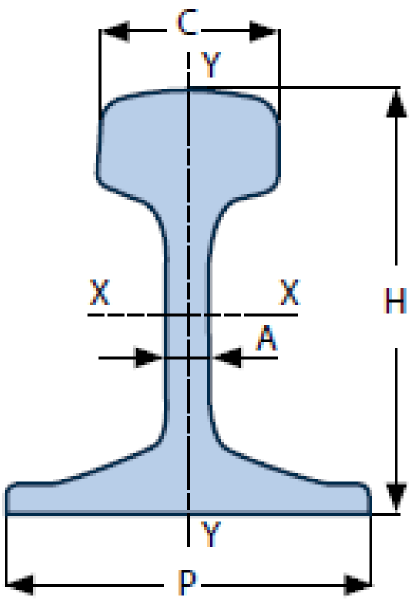
A modern steel rail has a flat bottom, and its cross section is derived from an I-profile. The upper flanges of the I-profile are converted to form the railhead. The English engineer Charles Vignoles has been credited the invention of this design in the 1830s [58].

Figure 8: Modern rail

A commonly utilized rail profile, especially in Europe is the UIC60 rail (with a Vignoles profile), where 60 refers to the section mass of the rail in kg per meter (kg/m).

EN 13674-1 2011 – Vignole railway rails 46kg/m and above

UIC 60



Rail Profile	60E1
Equivalent profile name	UIC 60
Section weight - (kg/m)	60.21
Rail height (H) - mm	172.00
Head width (C) - mm	72.00
Web thickness (A) - mm	16.50
Foot width (P) - mm	150.00

Table 1: UIC 60 Vignole rail profile

2.1.1.2. Rail pads

Rail pads are mostly found in railway tracks with concrete sleepers rather than those with wooden sleepers. Rail pads are elastic components that protect the sleepers from wear and impact damage as well as providing electrical insulation of the rails.

The importance of rail pads is highly appreciated from a track dynamics point of view, as they influence the overall track stiffness. When the track is loaded by the train, a soft rail pad permits a larger deflection of the rails and the axle load from the train is distributed over more sleepers. A stiff rail pad on the other hand, gives a more direct transmission of the axle-load, including high frequency load variations down to the sleepers below the wheels. [37]

Rail pads are placed between the rails and the sleepers as illustrated in Figure 9.

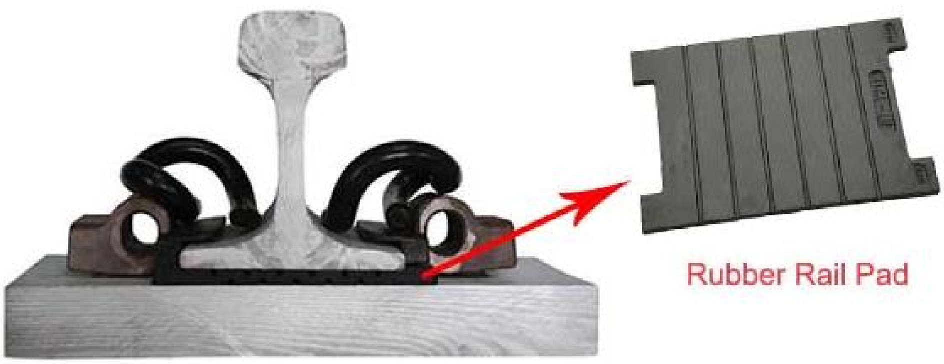


Figure 9: Rubber rail pad (adapted from AGICO Rail)

2.1.1.3. Fastenings

Rail fastenings are components with the main purpose of clamping the rail to the sleeper. Clamping assists in transferring lateral loads from the rail to the rest of the track by limiting horizontal movement. The choice of fastening greatly depends on the type of sleeper and geometry of the rail.

Elastic fastenings have gained popularity over the last decades with the introduction of continuous welded rail (CWR) as they offer resistance to lateral and longitudinal load and prevent track buckling. Examples of elastic fastenings commonly used are depicted in the figures below:

Pandrol fastening system

Vossloh fastening system

Figure 10: Elastic fastenings (adapted from Esveld, 2001)

2.1.1.4. Sleepers

Sleepers are load distributing components laid transversely on the track to provide support of the rails and preserve gauge, level, and alignment of the track. The sleepers also known as railway ties or crossties transmit vertical, lateral, and longitudinal forces from the rail down to the ballast bed. In most cases they also provide electrical insulation between the two rails.

Figure 11: Concrete sleeper

In the past, ever since the beginning of railway construction sleepers were mainly made from timber. With the development of steel tracks came the steel sleepers. Technological advances in the rail sector especially in axle load and train speeds gave rise to the concrete sleeper.

Today all three types of sleepers i.e., timber, steel and concrete are in use. In countries where the timber price is acceptable, timber sleepers are still frequently used. The reasons for timber selection are its cost effectiveness, corrosion resistance, workability, ease of handling, potential re-use and insulation. Concrete sleepers are ever getting popular and are generally considered more economical than timber sleepers for heavy haul and high-speed tracks. Concrete sleepers have much longer life (anticipated life of 50 years) than timber sleepers whose life varies from 8 to 30 years depending on timber species, quality and density of traffic, climate, and maintenance [61]. Nowadays, ballasted railway tracks are usually constructed with monobloc concrete sleepers. In some countries steel sleepers are preferred to timber sleepers as they provide greater lateral and longitudinal track resistance than timber sleepers (Birks et al., 1989) in addition they present sleeper life advantages.

2.1.1.5. Ballast

Ballast are coarse stones which are used to form the bed of the track. The main function of the ballast layer is to support the rails and the sleepers against vertical and lateral forces from the rail vehicles. In order to ensure structural integrity, ballast is tamped (tightly compacted) around the sleepers to keep the track precisely levelled and aligned. Sleepers to which the rails are fastened are embedded in the ballast.

2.1.1.6. Sub-ballast

The transition layer between the upper layer of coarse stones (ballast) and the lower layer of fine-graded subgrade is called the sub-ballast. The sub-ballast used in most new constructions is intended to prevent the mutual penetration of the subgrade and the ballast and to reduce frost penetration. Any sand or gravel materials may serve as sub-ballast material as long as they meet necessary filtering requirements.

2.1.1.7. Subgrade

Subgrade, or formation, is a surface of earth or rock levelled off to receive a foundation for the track bed. The sub-ballast and ballast layers rest on this material. The subgrade is a very important component in the track structure and has been the cause of track failure and poor track quality (Li, D. and Selig, 1995).

2.2. Rolling stock

Rolling stock refers to all railway vehicles, both powered and hauled, used either as power, trailer or engineering vehicles. A connected series of railway vehicles is what is commonly known as a train. Figure 12 illustrates main categories of the rolling stock.

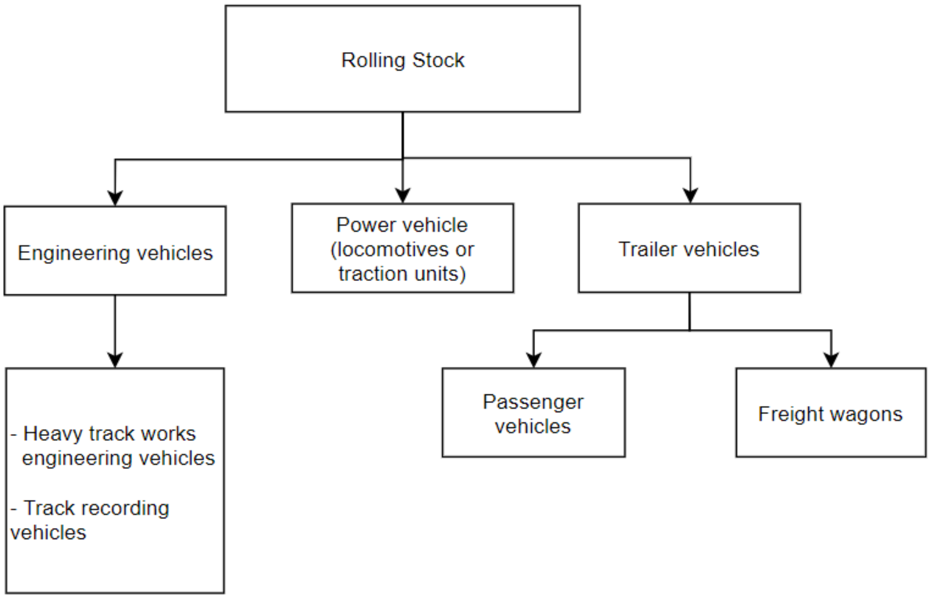


Figure 12: Rolling stock sub-system

Power vehicles are self-propelled which means they are equipped with traction motors and can either be locomotives or traction units. Locomotives are power vehicles with the sole purpose of hauling trailer vehicles. Their traction power can be steam, diesel, gas turbine or electric generated.

Trailer vehicles on the other hand are not self-propelled and serve the purpose of transporting passengers and goods.

Engineering vehicles are special vehicles used to perform track installation works and various track inspection and maintenance works.

All railway vehicles, either trailer or power consists of three basic parts:

i. Body shell or simply the vehicle body
ii. Bogies (truck)
iii. Wheelsets (axle and wheels)

2.3. Railway operation

Railway operation refers to all activities through which a railway company secures revenue service. Railway operation may be broken down into technical and commercial.

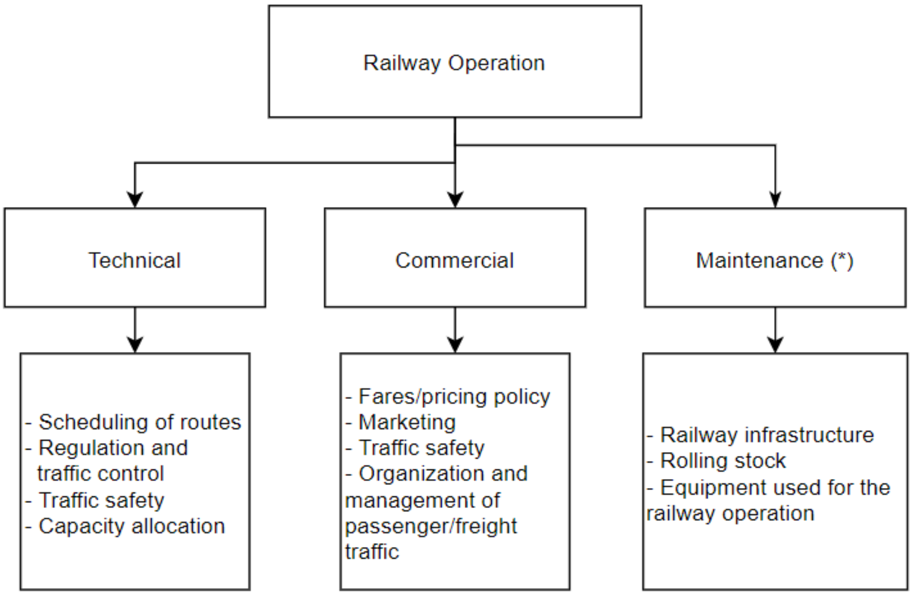


Figure 13: Railway operations sub-system

(*) Maintenance may also be categorized as part of railway operations, but it applies to all three constituents of the railway system, it is depicted as a 'horizontal activity' (Figure 13).

Recent trends in the railway system management have seen a major disaggregation of the state-owned incumbents who once covered all aspects of railway operations and has given rise to a series of individual companies, some remaining state-owned, some privately owned, each one carrying on certain roles within the industry.

In Europe, the railway industry has changed considerably since Directive 91/440/EC established the principle of splitting the unitary railways of Member States into mainly infrastructure providers and railway undertakings. Other players including vehicle keepers, entities in charge of maintenance (ECM) and regulatory bodies have also emerged within the railway operations context, (Table 2).

Infrastructure managers (IMs)	IMs are companies that maintain and manage railway infrastructure earning revenues from selling infrastructure access to railway undertakings. Infrastructure managers are not generally subject to competition.
Railway undertakings (RUs)	RUs are companies that operate and manage passenger or freight train operations for reward. Access to infrastructure is gained by requesting paths on the network and paying access charges to the IMS as the trains are run. Freight undertakings operate in an open market and compete for business.
Vehicle keepers	The vehicle keeper owns fleet of vehicles and exploit them economically by either using them as railway undertaking or hiring them out to other railway undertakings
Entities in charge of maintenance (ECMs)	ECMs are organisation charged with the maintenance and repair of vehicles. Being a relatively new entity in the legislation, there is an open market for companies to compete for vehicle maintenance and repair contracts as ECMs.
Regulatory bodies	national organizations responsible for regulation of the industry.

Table 2: Railway industry structure overview (European context)

A company can have several of the above roles (Table 2), and indeed many rail operators, particularly freight operators are railway undertakings, vehicle keepers and ECM.

3. Wheel – Rail interface

3.1. Introduction

Effective operation of rail vehicles is heavily dependent on small contact areas where the wheels meet the rails.

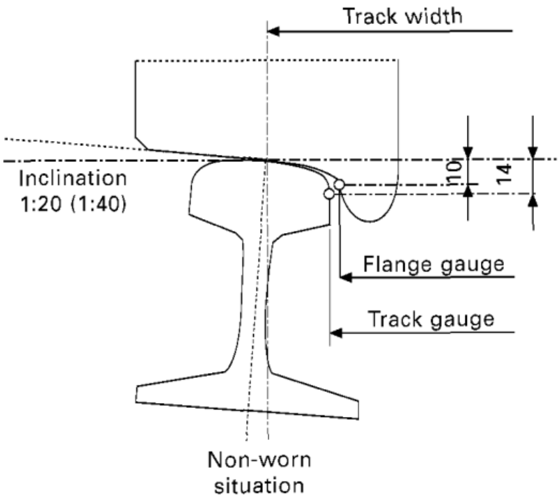


Figure 14 Wheel in contact with inclined rail (adapted from Shevtsov, 2008)

The rolling contact between the hard surfaces of the wheel and rail at these small contact patches ensures high energy efficiency and is what distinguishes the railway transportation from other modes of transports. However, several undesired phenomena may occur in this contact. High contact forces (vertical, lateral and longitudinal) induce stresses that may cause material yielding and fatigue. Rolling contact forces combined with friction induce wear. Situations of wheel and rail geometry irregularities and/or worn profile may arise resulting in poor vehicle dynamics and a further increase in contact forces and in vibrations and noise. From a low scale of consequences, phenomena at the wheel-rail interface may cause discomfort and disturbance for passengers. On a medium to high scale, increased maintenance costs for wheels and rails and other components may be the result. In severe cases, phenomena in the wheel-rail interface may lead to derailment induced by wheel or rail fracture or by the wheel flange climbing on the rail.

Therefore, a good understanding of the wheel-rail interface and its contact phenomenon is important to assure a safe and cost-efficient railway track. This chapter provides concepts of the wheel-rail interface that will be the backbone for the content addressed in the remaining part of this study.

3.2. Research fields

The wheel-rail interface and its contact phenomena are complex and subject of worldwide interdisciplinary research efforts. The complexity of the wheel-rail contact problem aggravates with the fact that it has little analogies with other engineering component contacts, which makes it difficult to transfer knowledge from other areas. Much of the complexity of the wheel-rail contact is brought about by the open nature of the system and hence the constantly varying environmental conditions.

Along a length of line, the position of the contact and its size and the resulting contact stresses also vary constantly and will be different, not just for each railway vehicle, but for each wheel as each, although starting with the same profile, will have worn by different amounts [5].

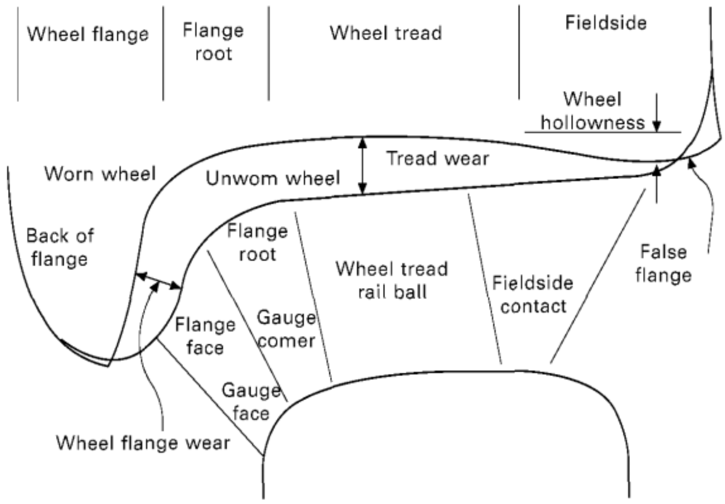


Figure 15: Wheel in new and worn states against new rail (adapted from Shevtsov, 2008)

Most research areas of interest in vehicle-track interaction from dynamic performance of the vehicle to maintenance of the infrastructure are widely based on the wheel-rail interface. The wheel-rail interface involves a number of research fields which can be categorized as:

i) Traditional fields – direct relation and dealing with the physical phenomena in the interface itself.
ii) Additional fields – indirect relation, they strongly affect the conditions in the wheel-rail interface or concern a maintenance strategy.

Table 3 reports some main research fields related to the wheel-rail interface with review on ongoing research.

Traditional Field	Contact Mechanics	This field of research involves forces and relative motion in the wheel-rail rolling contact. It addresses aspects of rolling contact such as Hertzian and non-Hertzian contact stresses, surface and subsurface stresses in the contacting bodies, elastic and plastic deformations, material shakedown and ratcheting and formation of residual stresses, together with thermal distributions and thermoelastic phenomena. A challenge in this area is to develop more reliable and efficient theoretical models and numerical methods for elastoplastic rolling contacts.
	Rolling contact fatigue (RCF)	Rolling contact fatigue manifests itself in crack formation and crack growth in the material close to, or at, the wheel-rail interface. Ongoing RCF research includes the search both for more advanced models capable of capturing more influencing factors and for faster models suitable for engineering applications.
	Material	Research on materials concerns both the refinement of existing materials and the development of new types of materials. Ideally, the 'best' combinations of material parameters are sought. The aim is to search for 'ideal' combinations of material parameters especially mechanical properties such as ultimate strength, fatigue strength, hardness, ductility, wear resistance, fracture toughness, crack threshold value and crack propagation parameters. The debate on the importance of these parameters for good wheel and rail performance is ongoing.
	Fracture mechanics	Fracture mechanics deals with the strength of cracked components. The studies in this field are useful in helping the railway sector to predict final fracture of infrastructure components such as the rail.

		Adapting fracture mechanics to the study of RCF (i.e. cracks in the wheel-rail interface) is far from straightforward. Complicating factors as compared to ‘plain’ fatigue crack growth analysis include complex (time-dependent) states of stress and strain, plastification, crack face friction and anisotropic material. Both fundamental and applied research with bearing on the wheel-rail interface is ongoing in this field.
	Tribology	This area of research is at the core of understanding and optimizing the wheel-rail interface. Both dry and lubricated friction are held important in the understanding of vehicle dynamics and traction as well as braking. Ongoing research concerns modelling of wear mechanisms and development and application of friction modifiers to combat corrugation and noise and to improve traction characteristics.
	Vehicle dynamics	Research in dynamics is exploited in the study of vehicle-track interaction. The results affect the behaviour of the wheel-rail interface and vice versa. Important areas of current research are vertical dynamics and also. vehicle-track behaviour in switches and crossings. Often, non-linearities in the wheel-rail interface, originating both in the track and in the vehicle, cannot be disregarded and call for numerically demanding calculations. Dynamic calculations combined with studies of corrugation, wear, fatigue, crack propagation and optimization are under development.
	Railway noise & vibration	Research on railway noise includes its generation and radiation and also its propagation to the surroundings and into passenger compartments. Rolling noise, induced by wheel and rail corrugation of wavelengths in the order 20-200 mm, continues to be a dominating problem. Development and implementation of measures to effectively and economically reduce noise at the source and at

		different locations along its propagation path is ongoing. The parallel area of vibration has similar features although the frequencies considered are much lower than for noise. Of special interest are phenomena occurring at high speeds in combination with soft clay in the underground where excessive vibrations can be encountered.
Additional fields	Management aspects and costs	The condition of the wheel-rail interface is an important part of the responsibilities of managers of the infrastructure and rolling stock. An obvious problem for many railways is that the rails and wheels are managed by different organizations. Also, laws and regulations may limit the scope for optimization. Nevertheless, the potential for cost savings should be exploited at all levels. New ideas for implementation of RAMS (reliability, availability, maintainability and safety) and LCC (life cycle cost) have been put forward in recent times.
	Maintenance – condition monitoring and predictive maintenance.	Condition monitoring of the wheel-rail interface means regular data collection and processing to plan optimal maintenance activities. For this purpose, implementation of modern technology with sophisticated sensors, computers and data transmission systems is underway. Important areas are effective systems for measuring profiles and detecting surface damage and also ultrasonic testing for internal defects in both wheels and rails. A problem here is to identify those defects and cracks which are potentially dangerous. Continued research efforts into these problems and new innovative products to serve the approximately 1 000 000 km of railway tracks and 25-50 million railway wheels in the world are needed

Table 3: Wheel-rail interface main fields of research [5]

With reference to Table 3. in this thesis research was done from the following fields:

i) Contact mechanics (traditional field)

- wheel geometry (profile) and rail geometry (profile) and their determination through measurements.
- ideal interaction of wheel and rail profiles that guarantee smooth running of vehicles on track – equivalent conicity.

ii) Vehicle dynamics (traditional field)

- Kinematic motion of wheelsets along the tangent track (hunting) given ideal wheel-rail interaction.
- Dangerous hunting due to defective wheel-rail interaction.

iii) Management aspects and costs (additional field)

- Repercussions of wheel-rail interface related defects and dangerous hunting in terms of reliability, cost, safety. RAMS and LCC models for track maintenance management.

iv) Maintenance (additional field)

- Innovative systems for wheel and rail profile measurements and condition monitoring. Bogie (truck) hunting inspection system case study for prediction of defective running behaviour of vehicle wheelsets.

3.3. Contact Mechanics

Contact mechanics is a physics field that addresses the interaction of solid surfaces and their deformation when they touch each other at one or more points. It is interested in defining contact area, pressure, stresses, and forces that occur when surfaces interact. From the railway perspective, the high energy efficiency of railway transportation is made possible by the favourably low losses in the rolling contact between the hard surfaces of the wheel and rail, which meet only in a very small contact patch. This contact is of paramount importance to the safe and efficient operation of a railway network.

The position of the wheel-rail contact varies continuously as a rail vehicle progresses down a section of track. The exact position depends on various factors, including:

- the wheel and rail profiles
- straight track or curved track - in the latter situation the degree of curvature of the track and whether the wheel is the leading or trailing wheelset on a bogie will affect the exact position of contact patch.
- other factors related to vehicle bogie design.

In his studies, Tournay (2001) categorized three possible regions of wheel-rail contact, (Figure 16 and Table 4).

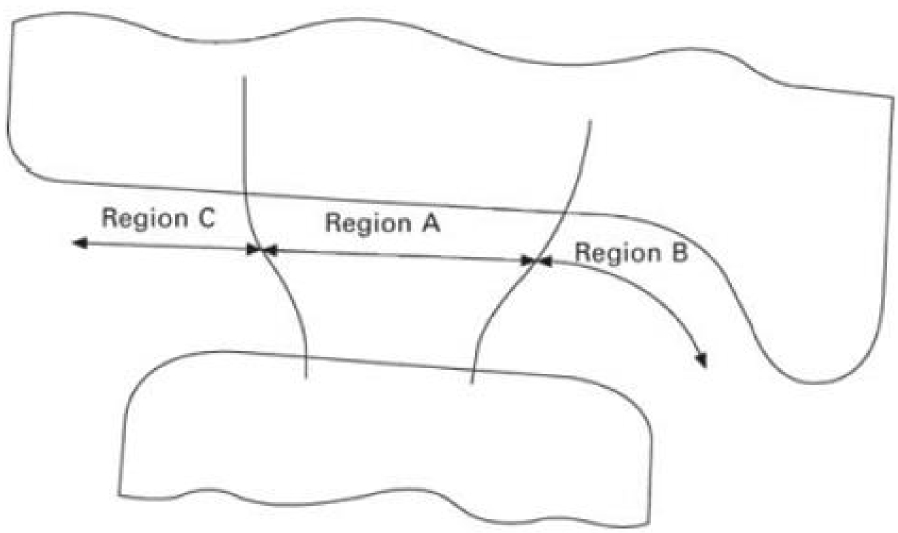


Figure 16: Wheel-rail contact regions (adapted from Tournay (2001)

Region	Wheel -rail contact	Description
A	Wheel tread-rail head	The wheel-rail contact is made most often in this region and usually occurs as the railway vehicle is running on straight track or very high radius curves. This region yields the lowest contact stresses and lateral forces
B	Wheel flange-rail gauge corner	The contact in this region is much smaller than that in region A and is often much more severe. Typically, contact stresses and wear rates are much higher. If high wear and material flow occurs, two-point contacts may evolve, where tread and flange contact is apparent
C	Contact between field sides of wheel and rail	Contact is least likely to occur here and, if it does, high contact stresses are induced, which will lead to undesirable wear features causing incorrect steering of the wheelset

Table 4: Wheel – rail contact regions and description

To be in a position to predict how wheel/rail profiles may evolve in time, a good comprehension of the contact stress is required. In this this study the scope is narrowed down to contact geometry, importance of contact stress in completing the wheel-rail contact problem is acknowledged but not addressed.

3.4. Wheel and rail profiles

The geometry of the wheel and the rail is highly influenced by the nature of the contact patch and the forces between a railway wheel and rail. The earliest railway wheels were cylindrical and ran on flanged rails. They were usually fitted to an axle so that both wheels could rotate independently [5]. Fitting the flanges to the wheels instead of the rails then came to existence as early as the 17th century. The position of the flanges was on the inside, outside, or even on both sides of the wheels, and was still being debated in the 1820s [37]. This evolution brought about considerable saving of material and most importantly allowed better guidance of the vehicle. Coning was then introduced partly to reduce the rubbing of the flange on the rail, and partly to ease the motion of the vehicle around curves. The modern wheelset came to being when the two wheels were joined to the axle and fixed to the vehicle body through bearings in axle boxes.

Wear at the wheel tends to change the wheel tread from an initial conical profile to a more complex concave shape. The shape of the profiles change as time progresses given the fact that the contact position is not spread evenly over the entire wheel or rail profile and as result of continuous wear and material flow. In order to be able to predict how profiles may evolve, a good understanding is therefore required of the contact stress.

Many railway organizations have designed 'worn' profiles, which are intended to maintain the same geometry as the wheel wears (examples include the UK P8 and the UIC S1002 profiles). Rails are mostly incline towards each other by a small angle, and this usually matches the conicity of the wheel so that the normal force with the wheelset in the central position is directed along the web of the rail. In the UK, this angle is 1 in 20 but 1 in 30 (for example in Sweden) and 1 in 40 (many countries including Germany) are also common.

The starting point for an analysis of wheel-rail contact is the identification of the size and shape of the contact patch. To do this for new profiles, drawings may be available but, after running for a little while, profiles will deviate significantly from the design case and it is essential to have accurate geometrical information of the worn profiles. To acquire these geometrical information measurements of wheel and rail profiles may be performed in accordance to governing standards.

3.4.1. Measuring the wheel and rail profiles.

To determine wheel and rail geometry precise measurements can be made using mechanical or laser devices. The DMA's wheel profile measurement system (WPMS) and rail profile measurement system (RPMS) are world-class examples of non-contact laser-based systems that enable a highly detailed condition assessment of wheel and rail geometries, respectively.

The WPMS is a wayside monitoring system that generates the entire wheel profile using one internal and one external measurement device, for each of the two wheels. The measurement principle deployed is based on the 'laser triangulation' technology, where the laser source projects a beam of light on a cross section of the wheel and the cameras capture the image of that section of interest.

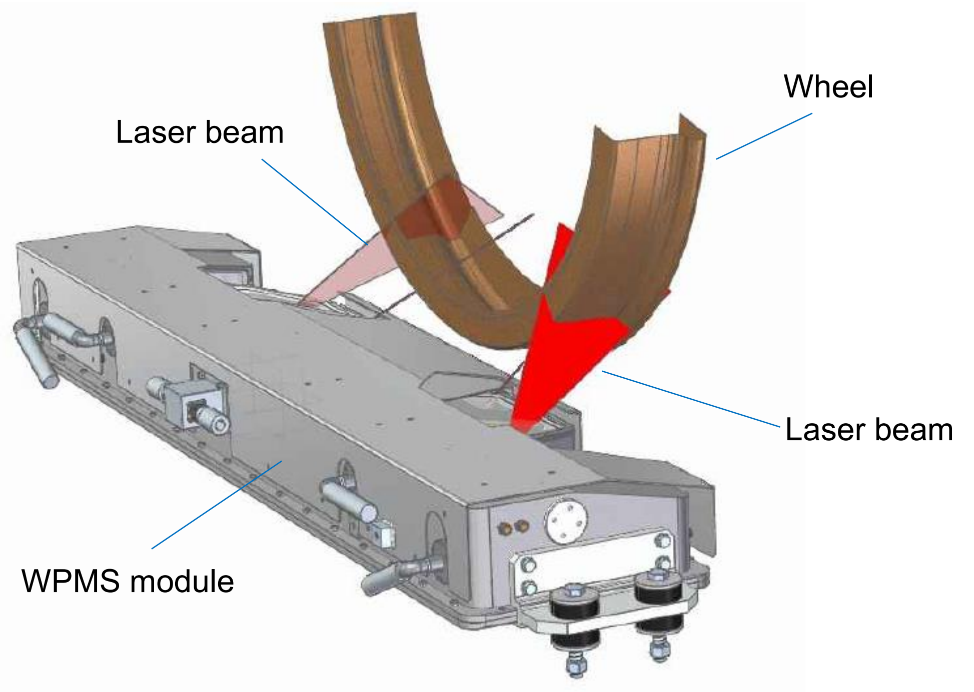


Figure 17: DMA wheel profile measurement system (WPMS)

Mathematical algorithms are then applied to process the image and deliver the accurate Y and Z coordinates of the acquired profile. Typical measured wheel profile is illustrated in Figure 18.

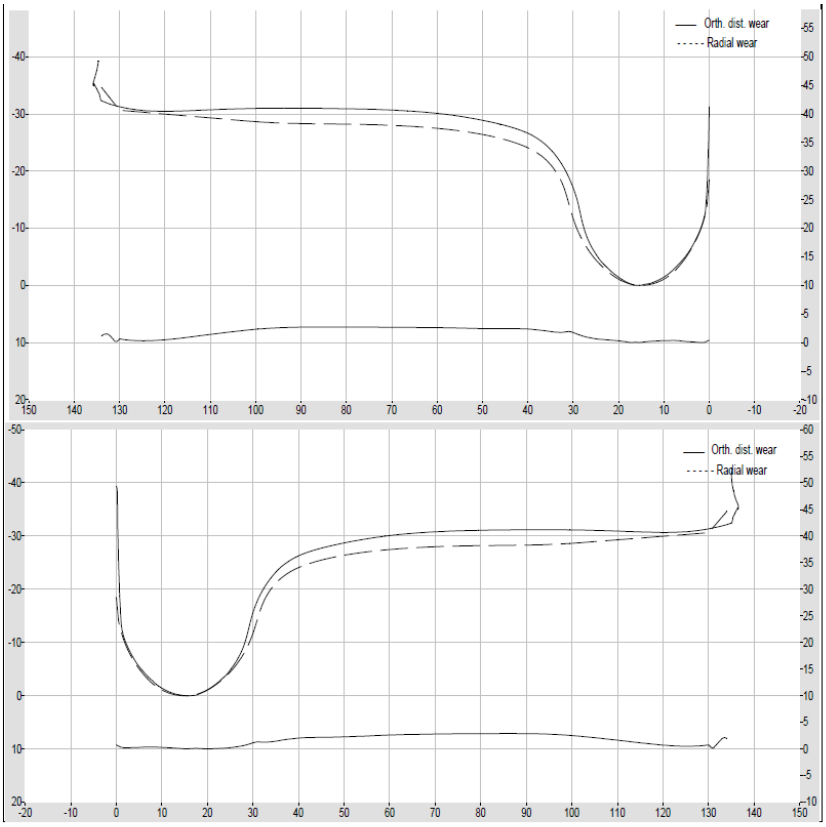


Figure 18: Wheel profile (worn).

The RPMS on the other hand is a train borne monitoring system that generates the entire rail profile given that the external and internal measurement module per rail configuration is adopted. In this case four measurement modules are present, one dedicated to each side of the rail, as shown in the figure below.

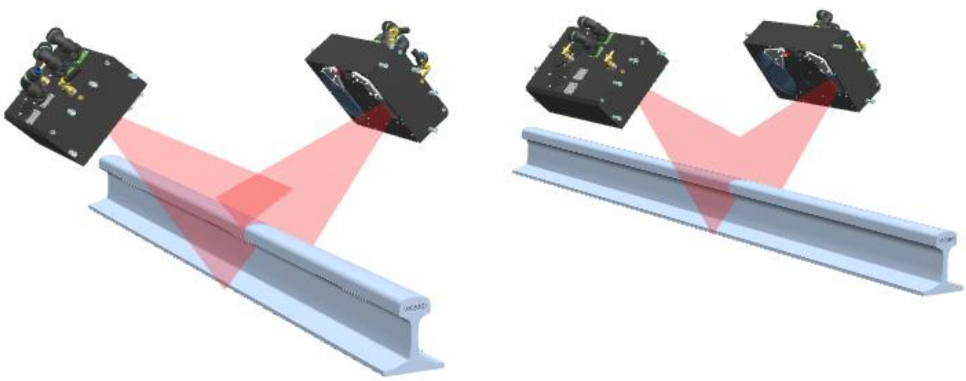


Figure 19: DMA rail profile measurement system (RPMS)

Similarly, to the WPMS, the measurement principle deployed for the RPMS is the ‘laser triangulation’. The laser source projects a beam of light on a cross section of the rail and the cameras capture the image of that section as shown in the figure below.

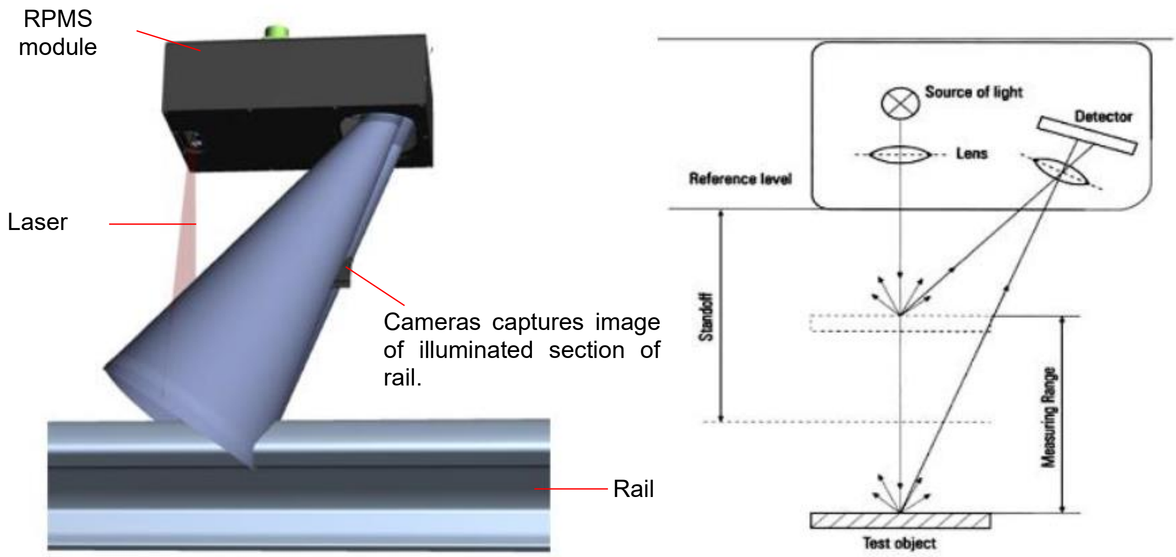


Figure 20: Laser triangulation principle deployed for wheel and rail profile measurements.

Mathematical algorithms are then applied to process the image and deliver the accurate Y and Z coordinates of the acquired profile. Typical measured rail profile is illustrated in Figure 21.

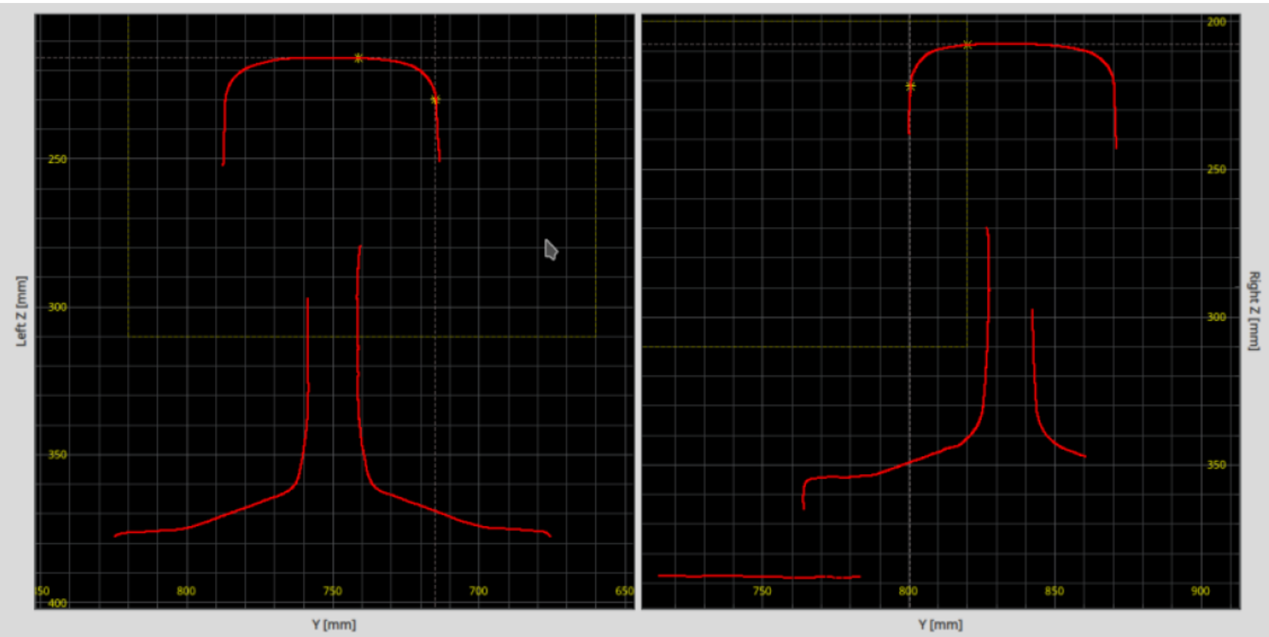


Figure 21: Rail profile

3.5. Vehicle Dynamics

One of the most complicated dynamical systems in engineering is the railway train running along a track. This system entails many bodies and thus various degrees of freedom. In addition to this, the many bodies comprise the rail vehicle and a moving interface connects the vehicle with the track. This interface involves the complex geometry of the wheel tread and the rail head and nonconservative frictional forces generated by relative motion in the contact area.

In the late 18th and early 19th century, development in rail vehicle dynamics was concentrated on the prime mover and the possibility of traction using adhesion. Guidance was an issue and was not resolved until the almost universal adoption of the flanged wheel in the early 19th century. The first simple mathematical models of the action of the coned wheelset were introduced by Redtenbacher and Klingel in the late 19th century.

The growing size of the steam locomotive increased the problem of the forces generated in negotiating curves, and in 1883 Mackenzie gave the first essentially correct description of curving. This became the basis of a standard calculation carried out in design offices throughout the era of the steam locomotive. As train speeds increased, problems of ride quality, particularly in the lateral direction, became more important. The introduction of the electric locomotive at the end of the 19th century involved Carter, a mathematical electrical engineer, in the problem, with the result that a realistic model of the forces acting between wheel and rail was proposed and the first calculations of lateral stability carried out [37].

The increasing speeds of trains and the greater potential risks arising from instability has posed greater challenges on the scientific approach to vehicle dynamics in the last decades. As the power of the digital computer increased so did the scope of engineering calculations, leading to today’s powerful modelling tools.

In this thesis, the approach adopted is confined to the kinematics of wheelset running behaviour on the track with the quest to provide initial performance information of vehicle running behaviour. To enrich this understanding concepts of vehicle dynamics, are required to understand phenomena at the wheel-rail interface as well as effects on vehicle stability which is further developed in the subsequent chapter. Vehicle dynamics is a paramount and vast topic closely related to the subject matter of this thesis but that is excluded from the scope of this work for simplicity purposes of the thesis work.

3.6. Modern wheelset running behaviour on the track

The modern railway wheelset consists of two coned wheels with flanges mounted on a common axle and fixed to the vehicle body through bearings in axle boxes (Figure 22).

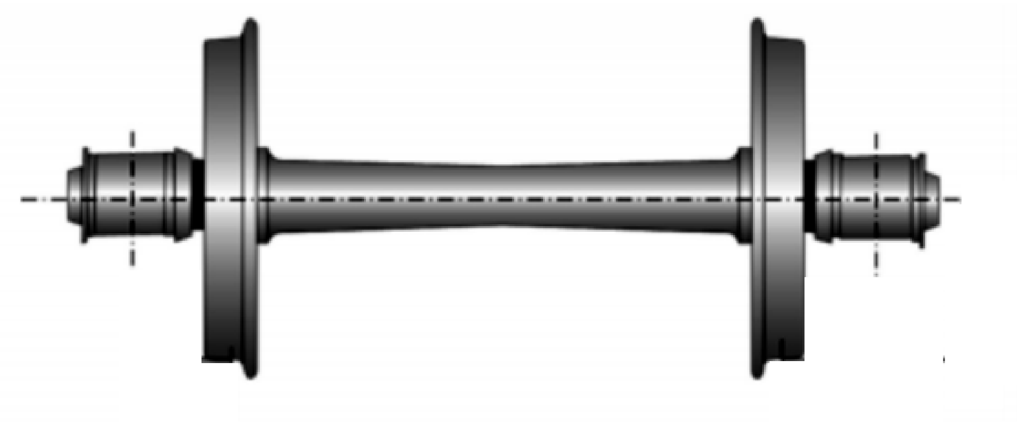


Figure 22: Railway wheelset

This configuration allows each wheel to rotate with a common angular velocity and a constant distance between the two wheels is maintained. The flanges are on the inside edge of the treads and the flangeway clearance allows, typically ±7 to ±10 mm of lateral displacement to occur before flange contact [15].

3.6.1. Conicity of wheels

Coning of the wheels is an important aspect contributing to the correct running of wheelsets on the track. It minimizes the occurrence of the flange rubbing on the rail and eases the motion of the vehicle around curves.

New wheelsets are commonly designed with purely coned treads, typically coned at 1/20 or 1/40. However, the interaction between wheels and rails when vehicle runs on the track causes wear. Tread wear modifies wheel profile such that treads come to possess curvature in the transverse direction. This effect is similarly experienced on the rails. Wear of wheels and rails influence the behaviour of the railway vehicle as a dynamic system.

George Stephenson in his “Observations on Edge and Tram Railways” stated the following regarding coning of the wheel tread:

> *It must be understood the form of edge railway wheels are conical that is the outer is rather less than the inner diameter about 3/16 of an inch. Then from a small irregularity of the railway the wheels may be thrown a little to the right or a little to the left, when the former happens the right wheel will expose a larger and the left one a smaller diameter to the bearing surface of the rail which will cause the latter to lose ground of the former but at the same time in moving forward it gradually exposes a greater diameter to the rail while the right one on the contrary is gradually exposing a lesser which will cause it to lose ground of the left one but will regain it on its progress as has been described alternately gaining and losing ground of each other which will cause the wheels to proceed in an oscillatory but easy motion on the rails* [27]:

The rolling behaviour of the wheelset suggests why conicity of wheels was adopted. If the flange is on the inside the conicity is positive and as the flange approaches the rail there will be a strong steering action tending to return the wheelset to the centre of the track.

If the flange is on the outside the conicity is negative and the wheelset will simply run into the flange and remain in contact as the wheelset moves along the track.

Moreover, considering motion in a sharp curve in which the wheelset is in flange contact. If the flange is on the inside, the lateral force applied by the rail to the leading wheelset is applied to the outer wheel and will be combined with an enhanced vertical load thus diminishing the risk of derailment. If the flange is on the outside, the lateral force applied by the rail is applied to the inner wheel, which has a reduced vertical load, and thus the risk of derailment is increased.

3.6.2. Kinematic oscillation of wheelsets

A wheelset rolling along the track may normally be subjected to a slight lateral displacement to one side. In this condition the wheel on one side is running on a larger radius and the wheel on the other side is running on a smaller radius. As wheels are mounted on a common axle, one wheel will move forward faster than the other due to the instantaneous larger rolling radius. Therefore, if pure rolling is maintained, the wheelset moves back in to the centre of the track, with a steering action that is enabled by the coning. However, the wheelsest overshoots the centre of the track and the result is a weaving oscillation [15].

In 1883 Klingel gave the first mathematical analysis of this kinematic oscillation, Figure 23.

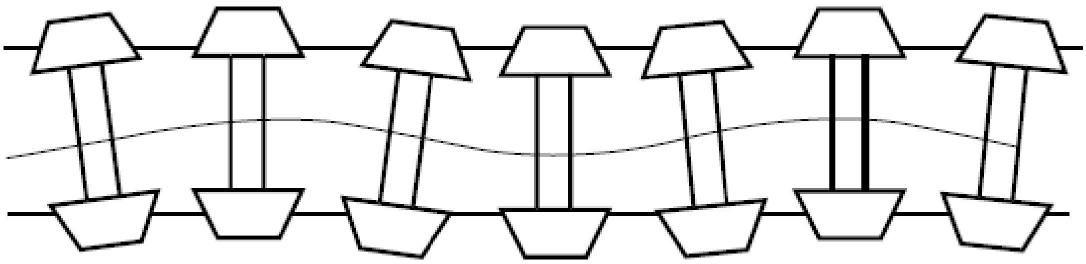


Figure 23: Kinematic oscillation of a wheelset

In his analysis, he derived the relationship between the wavelength, the wheelset conicity, wheel radius and the lateral distance between contact points.

In the International Union of Railways (UIC) specification UIC 519 – 2004 which has been incorporated in the European standard EN 15302, Klingel's formula is derived for the kinematic movement of a wheelset under the following assumptions:

- free wheelset motion (no damping and no flange contact)
- no inertia
- constant forward speed.
- conical profile of wheels

Under these assumptions the kinematic movement of a free wheelset is described by the following differential equation:

$$\ddot{y} + \frac{V^2}{er_0}\Delta r = 0$$

The forward speed being constant, this is expressed as:

$$V = \frac{dx}{dt}$$

Therefore, the change of the lateral displacement in time is expressed as:

$$\frac{dy}{dt} = V\frac{dy}{dx} \quad \text{and} \quad \frac{d^2y}{dt^2} = V^2\frac{d^2y}{dx^2}$$

This differential equation becomes:

$$\frac{d^2y}{dx^2} + \frac{\Delta r}{er_0} = 0$$

The conical profile of wheels assumption has that the conical profile angle γ is introduced, Figure 24.

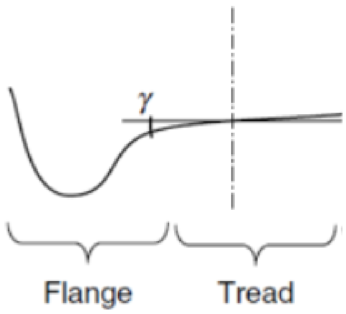


Figure 24: wheel conical profile angle

Then:

$$\Delta r = 2y\ \tan\gamma$$

Substituting the last equation to its precedent one, the differential equation becomes:

$$\frac{d^2y}{dx^2} + \frac{2\tan\gamma}{er_0}y = 0$$

This is a second order differential equation with constant coefficients whose solution is a sinewave with a wavelength λ of which is commonly known as the Klingel's formula:

$$\lambda = 2\pi\sqrt{\frac{er_0}{2\tan\gamma}}$$

Equation 1: Klingel's formula

Where:

- λ-wavelength
- tan γ – wheel conicity (conical profile)
- e – distance between contact points (approximately 1500mm for standard gauge)
- r_0 – radius of wheels when wheelset is centered on track

Klingel's formula shows that as the speed is increased, so will the frequency of the kinematic oscillation. Any further aspects of the dynamical behaviour of railway vehicles must be deduced from a consideration of the forces acting, which is beyond the scope of this study.

3.7. Equivalent conicity

In the case where wheels do not have a conical profile (due to design or wear in service) linearization methods (Figure 25) are required with the condition that the linear differential equation can still be applied by replacing tan γ with $\tan\gamma_e$, which is called the "equivalent conicity", [1].

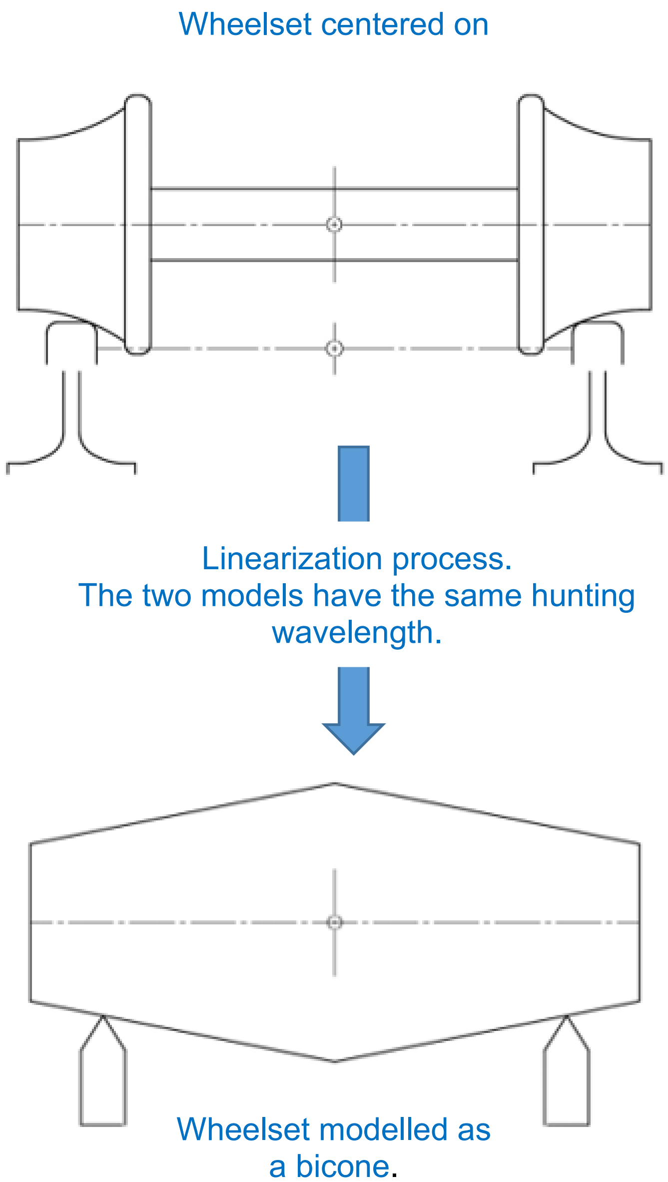


Figure 25: Linearization model of wheelset motion – equivalent conicity

EN 15302 provides a definition of the equivalent conicity as:

- *The equivalent conicity is equal to the tangent of the cone angle* $\tan\gamma_e$ *of a wheelset with coned wheels whose lateral movement has the same kinematic wavelength as the given wheelset (but only on tangent track and on large-radius curves).*

The main technical specifications/standards developed regarding the equivalent conicity are UIC518, UIC519 and EN15302. These specifications/standards have defined the calculation method of equivalent conicity and established the equivalent conicity limit for different running speed levels and different line conditions.

The equivalent conicity of a defined wheelset running on a defined track depends on:

- the distance between active faces of both wheels (back-to-back),
- the two wheels' profile,
- the two rails' profile
- the distance between both rails (track gauge),
- the inclination of the rails.

3.7.1. Determining the equivalent conicity.

The International Union of Railways leaflet UIC 519 defines a calculation method for determining the equivalent conicity associated with the lateral movement of a wheelset on a track for any given wheel and rail profile (theoretical or real).

The following assumptions are adopted in the quest to calculate the equivalent conicity as defined by EN 15302:

- Both the wheel and the rail are considered rigid,
- A theoretical wheel is symmetrical in revolution,
- A theoretical rail is straight and is represented by a single profile,
- A real rail is defined by at least 11 profiles regularly spaced apart over a 100 m section of line; the conicity is obtained by taking the average of these individual conicities, the standard deviation of which should also be indicated.
- The wheel does not penetrate into the rail only point contacts are considered.
- No account is taken of an axle's roll (rotation about an axis longitudinal to the track) as the wheelset moves laterally on the track
- At the point of contact, the tangent planes to the rail and to the wheel are parallel

To determine the equivalent conicity ($\tan\gamma_e$), EN 15302 then provides the subsequent procedure:

1) Determine the wheel and rail profiles, either by measurement for real profiles or by a theoretical calculation for theoretical profiles.
2) Determine the Δr = f(y) characteristic giving, for each lateral movement y of the wheelset on the track, the difference between the right-hand and the left-hand rolling radii Δr = r1-r2.
3) Determine the equivalent conicity for a lateral movement ŷ of the wheelset on the track.

The determination of wheel and rail profiles by measurement is the first step. An overview of this step was provided in the previous chapter with examples of the DMA measurement systems WPMS (wheel profile measurement system) and RPMS (rail profile measurement system). The second step is the determination of the rolling radius difference which is addressed in the following section.

3.7.2. Rolling radius difference (Δr)

In pure rolling motion of a railway vehicle wheelset along the track, the vehicle may be subjected to small lateral displacement (y) to one side. The wheel on one side will run on a larger radius and the wheel on the other side will run on a smaller radius (Figure 26).

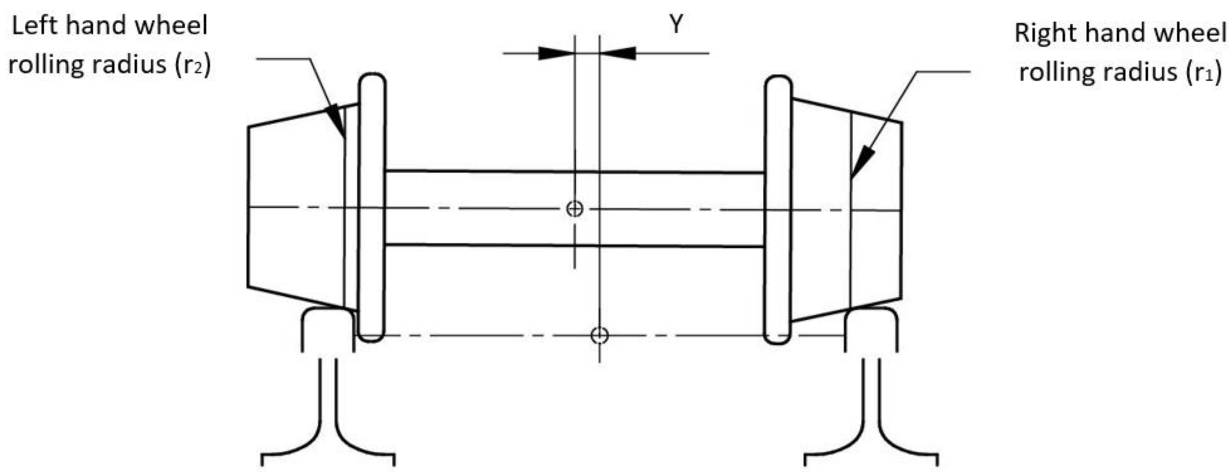


Figure 26: Rolling radius description

The rolling radius difference ($\Delta r = r_1 - r_2$) is simply the difference between the right-hand wheel rolling radius and the left-hand wheel rolling radius as the wheelset moves laterally on the track.

Rolling radius is the radius of the rail vehicle wheel measured from center to tread. The right-hand wheel rolling radius is denoted r1 while the left-hand one is r2 as defined in the UIC 519.

Given the track coordinate system as defined in the standard EN 13848-1 is as follows:

- X axis: axis represented as an extension of the track towards the direction of running.
- Y axis: axis parallel to the running surface.
- Z axis: axis perpendicular to the running surface and pointing downwards.

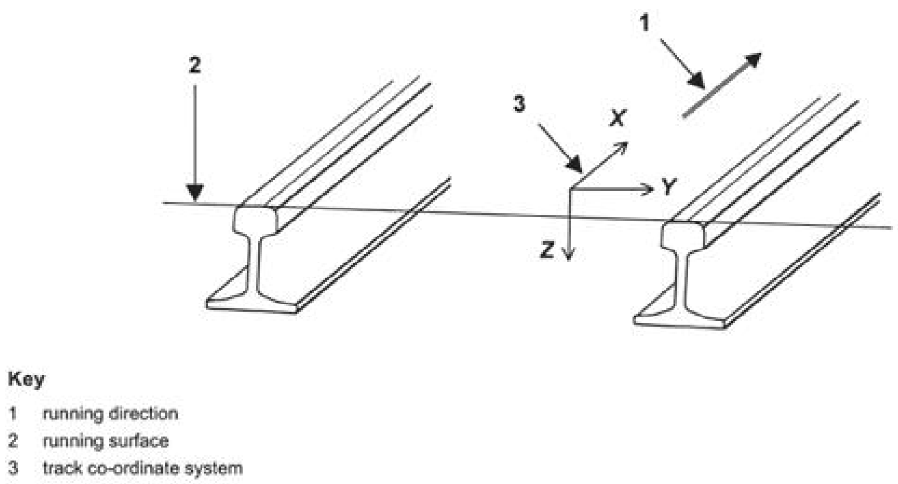


Figure 27: Railway track coordinate system (adapted from the EN 13848-1 : 2003)

The displacement of wheelset in the lateral direction of the track is denotated as Y, (Figure 26).

When the wheelset moves laterally on the track the contact points on the wheel are displaced in different ways depending on the wheel and rail profiles as illustrated in the figure below.

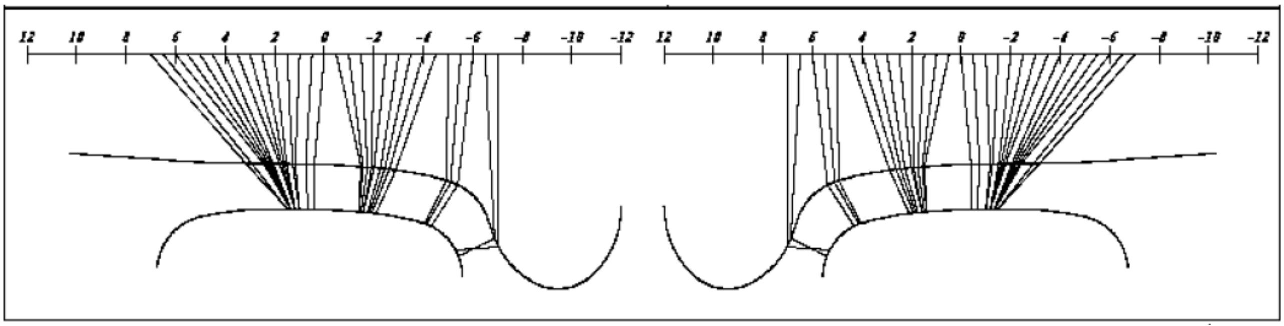


Figure 28: Contact points wheel-rail interaction for wheelset lateral motion on track

Left and right rolling radius difference versus wheelset lateral movement can be plotted from the knowledge of the contact points for wheelset lateral motion on the track.

This function is called the rolling radius difference function (Figure 29).

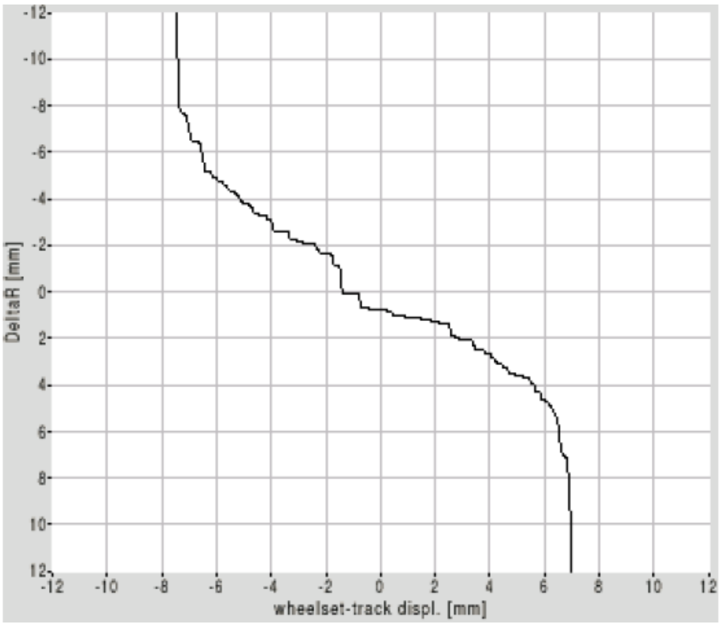


Figure 29: Rolling radius difference (Δr) versus wheelset lateral movement

The rolling radius difference function (Δr) dominates the dynamic behaviour of railway vehicles especially in stability, steering ability, and contact stress and thus has a great effect on the stability of hunting movement.

3.7.3. Calculation of equivalent conicity ($\tan\gamma_e$)

From the actual movement of the wheelset, the equivalent conicity may be calculated in two ways (UIC 519).

i) either by applying the Klingel formula

ii) or by applying a least-squares type linear regression to the portion of the Δr = f(y) characteristic within the 2y interval. The slope of this regression is equal to 2 $\tan\gamma_e$

The equivalent conicity can therefore be seen as an average of the slope of the Δr function in a given range of lateral displacement. The figure below illustrates the presentation of the Δr - rolling radius difference function (big graph) and the $\tan\gamma_e$ - equivalent conicity function (small graph).

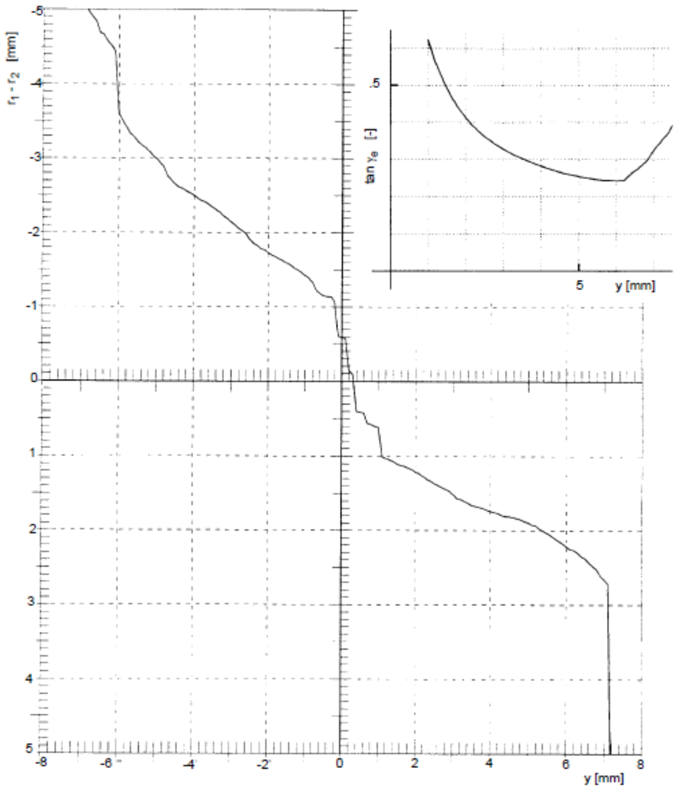


Figure 30: Δr function and $\tan\gamma_e$ representation (adapted from UIC 519 – 2004)

The equivalent conicity plays an essential role in the wheel-rail interface as well as the dynamic running behaviour of a rail vehicle as it allows optimal appreciation of wheel-rail contact on tangent track and on large radius curves [68]. This makes it a pivotal concept in this study, and especially in the bogie hunting phenomenon addressed in the next chapter.

4. Bogie lateral instability –‘hunting’ problem

As seen throughout this study, the rails provide support and lateral guidance to railway vehicles for a smooth running along the track. Rails and switches change the rolling direction of wheels hence determining the travelling direction of the vehicle. However, a good construction of the track superstructure does not guarantee on its own a smooth running of the railway vehicle, for achievement of the desired vehicle-track performances, design and construction of the rolling stock is of equivalent importance. From the vehicle perspective, the running gear composed of wheelsets with axle boxes, elastic suspension and the traction system is what guarantees safe motion of the vehicle along the railway track. Depending on the running gear the vehicles may be described as bogied or bogie-less [37].

In literature the term bogie sometimes is used simply to denote a construction that supports the car body without including the wheelsets. However, and this is usually the correct definition, the term refers to the total of ‘secondary suspension – bogie frame and primary suspension – wheelsets’. The latter definition of the bogie is the one adopted in this study.

In vehicles without bogies the suspension, brakes, and traction equipment are mounted on the car body frame. Such vehicles are limited in length as the ability of the inscription of a vehicle in curves depends directly on the length of the vehicle and were common in the past. The evolution of the railways meant an increase in vehicle’s capacity which consequently implied increase in vehicles’ length that could no longer be feasible on car body mounted running gear. Running gear mounted on a separate frame that can turn relative to the vehicle body is known as a bogie (or truck). Nowadays, bogie vehicles are more common than conventional two axle-vehicles. Evolution in design has had bogies pass from simply allowing the running gear to turn in a horizontal plane relative to the car body thus making it possible for the wheelsets to have smaller angles of attack in curves to modern bogies with the capacity to transmit all the longitudinal, lateral, and vertical forces between the car body and the wheelsets.

In this chapter, bogie stability in tangent (straight) track relative to wheel-rail interface parameters is addressed.

4.1. Functions of the bogie

In their design, bogies should provide for the following functions:

- Assist the optimum transfer of loads from the car body to the rails.
- In curved tracks, bogies should guarantee the smooth inscription of the wheelsets.
- In tangent track, bogies should guarantee stability of the vehicles (crucial for high-speed train applications).
- Provide dynamic comfort to in all three directions - vertical (z), lateral (y) and longitudinal (x).

4.2. Bogie components

A modern bogie is composed of the following main components:

i) Wheelsets (wheels and axle)
ii) Axleboxes
iii) Suspension
iv) Dampers

In other applications, bogies may also carry braking equipment and lubrification devices.

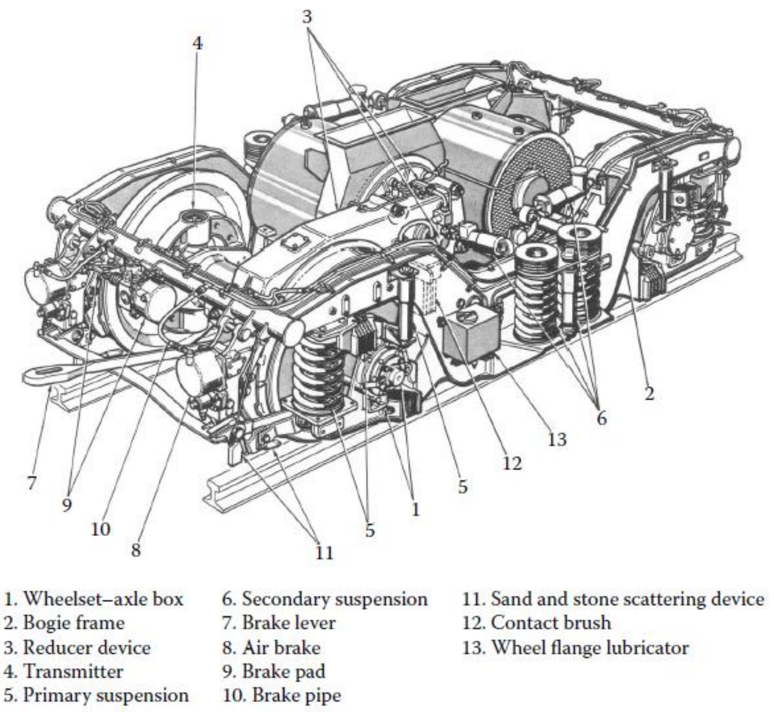


Figure 31: Conventional bogie – main parts (adapted from Schneider Jeumont Rail. no date, Bogie CL93 à Moteurs Asynchrones, *Catalogue pieces de rechange*, Le Creusot, France)

The geometrical and technical characteristics of the bogie components that substantially affect the dynamic behaviour of the vehicles are (Joly, 1983)

- The longitudinal (Cx) and lateral (Cy) stiffness of the primary suspension springs
- The bogie wheelbase
- Wheel diameter
- Mass of the bogie and wheelsets
- Equivalent conicity of wheels

All the above parameters directly influence the lateral behaviour of the bogies which is the scope of this chapter.

4.2.1. Wheelsets

Wheelset comprises two wheels rigidly connected by a common axle. Various designs of wheelsets are present in the railway applications depending on type of vehicle (power vehicle or trailing vehicle), type of braking system, position of bearings on axle etc. Common designs of wheelsets are depicted in the figure below.

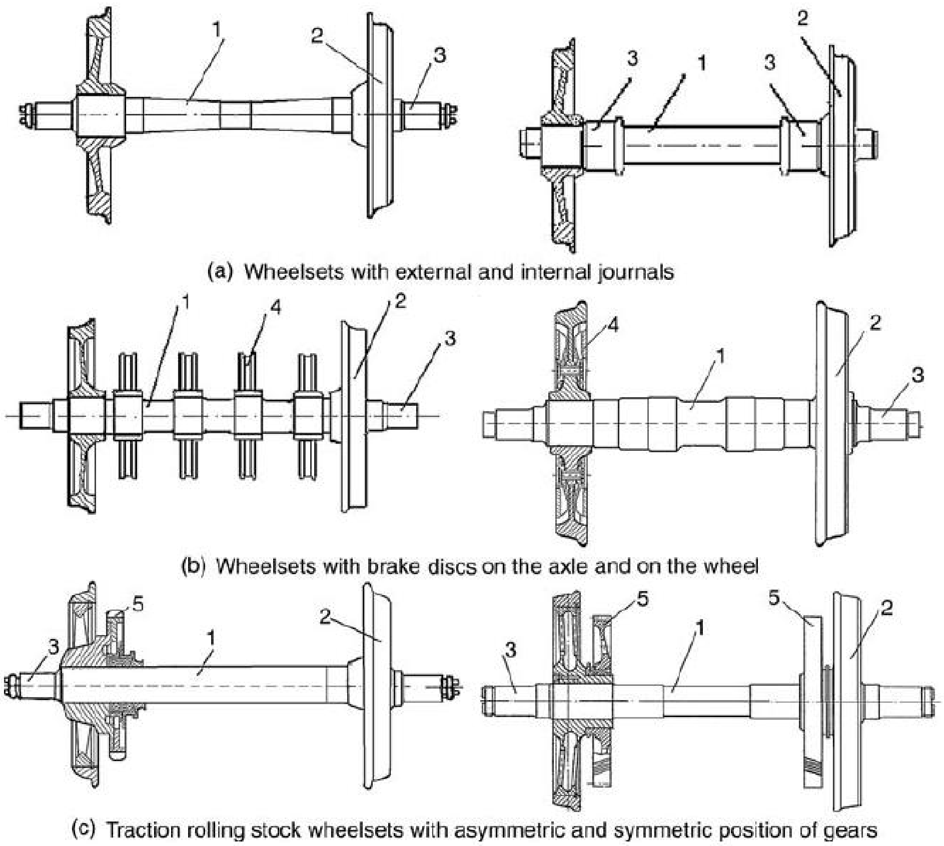


Figure 32: Main types of wheelset designs [37]

Despite the variety of designs, all wheelsets have two common features: the rigid connection between the wheels through the axle and the cross-sectional profile of the wheel rolling surface, named wheel profile.

4.3. Concept of bogie hunting

Klingel's analysis of the kinematic oscillation of a rail vehicle wheelset assumes a harmonious motion without damping and without flange contact, thus a pure kinematic analysis. In real applications, the motion of a railway wheelset and particularly of a whole vehicle (car body + bogies) is much more complex (Esveld, 2001).

Carter presented the first realistic model of lateral dynamics of a railway vehicle. [63]. In this model, Carter introduced the fundamental concept of creep and included the effect of conicity and showed that the combined effect of creep and conicity could lead to dynamic instability which is what is commonly referred to as hunting. In his 1916 paper, Carter stated that the forces acting between wheels and rails can be assumed to be proportional to the creepages. The concept of creep had first been described by Osborne Reynolds in relation to the transmission of power by belts or straps, and he noted that the concept was equally applicable to rolling wheels [45].

Carter derived equations of motion for the rigid bogie in which two wheelsets were connected by means of a stiff frame. They consist of the two coupled second-order linear differential equations in the variables lateral displacement (y) and yaw angle (ψ) of the bogie and they are equivalent to

$$m\ddot{y} + 4f(\dot{y}/V - \psi) = Y$$

$$4f\lambda l y/r_0 + I\ddot{\psi} + 4f(l^2 + h^2)\dot{\psi}/V = G$$

Equation 2: Carter's equations of motion for rigid bogie

where m and I are the mass and yaw moment of inertia of the bogie, f is the creep coefficient (the creep force per unit creep), h is the semi-wheelbase of the bogie and V is the forward speed.

From Carter's equations it can be deduced that lateral displacements of the wheelset generate longitudinal creep. The corresponding creep forces are equivalent to a couple that is proportional to the difference in rolling radii or conicity, and which tends to steer the wheelset back into the centre of the track. This is the basic guidance mechanism of the wheelset. Furthermore, a lateral creep force is generated when the wheelset is yawed. In effect, this coupling between the lateral displacement and yaw of the wheelset represents a form of feedback, and the achievement of guidance brings with it the possibility of instability.

Recapitulating on results from Carter's work, it can be said that hunting is highly dependent on vehicle speed, friction creep characteristics and the equivalent conicity of wheel on the rail. When the forward speed of a vehicle increases beyond a certain limit (depended on lateral and yaw coupling of the vehicle), the steady motion loses its stability and hunting begins. Friction level is important as the coefficient of friction limits the tangential force that can be sustained by the wheel-rail contact and a modest coefficient of friction is required to guarantee stability. High equivalent conicities also increase the risk of bogie instability. Factors such as wheelset yaw and track irregularity also reinforce hunting. The resulting vibration must remain acceptable to provide avoid ride discomfort and meet safety requirements [21].

Therefore, hunting can lead to ride discomfort from a low-risk perspective and eventual deterioration of both wheels and rails that may cause derailment from a high-risk perspective if vehicle speed exceeds a certain operating speed. The speed at which the railway vehicle becomes unstable is called *critical speed*. Below the critical speed the motion is damped out but above the critical speed, the vehicle is subjected to much higher forces due to the increasing oscillating motion and to the collision between wheel flange and the rail.

The critical hunting speed is highly dependent on the vehicle/track characteristics. When vehicle hunting is onset, the displacements of wheelset are generally large, alternatively flanging from one side of the rails to the other. Considering the wheel/rail geometry and the creep force saturation, the vehicle/track system under hunting conditions is usually treated as nonlinear system. Vehicle simulation computer models, which include the processes to solve these equations of motion, are often used to predict the hunting speed. Track tests are also generally required to either validate the hunting speed predicted by modelling or ensure the system operating speed is below the hunting onset speed.

The effective conicity of wheel – rail contact has considerable influence on the vehicle hunting speed. As wheelset conicity increases, the onset critical speed of hunting decreases. For this reason, it is important when designing wheel and rail profiles to ensure that, for a specific bogie/vehicle, the critical hunting speed is above the operating speed.

The hunting phenomenon above critical speeds leading to vehicle instability and higher probability of derailment needs to be well understood and managed to guarantee a reliable, safe, and cost-effective railway service not only by rail operators but also by infrastructure managers. The hunting problem is commonly considered as a vehicle-borne problem and has been confronted mainly by the rail operators through bogie and suspension design improvements while infrastructure managers have shown lesser interest in addressing it.

Most research work done in this area has been biased towards vehicle dynamics and with the scope of enhancing vehicle performance. Wickens [22] provided an early study in this matter, in which he investigated the dynamic stability of railway vehicle wheelsets and bogies having profiled wheels. It was shown that the dynamic instability of railway vehicle bogies and wheelsets is caused by the combined action of the conicity of the wheels and the creep forces acting between the wheels and the rails. N. K Cooperider *et al* studied wheelset instability by application of the modified nonlinear creep force to obtain the effects of longitudinal and lateral damping forces, tread slope and wheel-rail clearance on the bogie stability [24]. The research of True H [26] focuses on evaluation of the stability of railway vehicles given the nonlinear critical velocity. Polach O et al. [25] proposed a stability evaluation criterion based on bifurcation theory. All these examples of research are directed towards the vehicle side rather than the infrastructure.

Less focus has been placed on the track response and deterioration mechanism in the long run regarding the hunting problem. However, this should not be the case. There is need for IMs to increase their interest and involvement in understanding how bogie performance wheelset running on the rails can influence track safety, the degradation of the track and account for increased maintenance. From the infrastructure manager (IM) point of view, which is the perspective adopted in this study, equivalent conicity is the principal parameter in analysis of the wheel-rail interface and in addressing the hunting problem.

4.4. Influence of equivalent conicity to hunting problem.

Infrastructure factors that influence the dynamical behavior of rail vehicles include track layout, track geometric quality and the wheel-rail contact geometry. For what concerns bogie stability on a tangent track, the wheel-rail contact geometry parameter – equivalent conicity is the most relevant.

Given the fact that hunting highly depends on vehicle speed and equivalent conicity, the ideal way to control the risk of hunting would be to assess the stability of a vehicle at maximum speed up to a defined value of conicity and ensure that this value is not exceeded in normal service at maximum speed.

However, the control of the real equivalent conicity experienced by a vehicle during its operation is still not feasible, because its determination requires both vehicle and track data. In the modern railway industry setup this is a well-known data integration and management problem as the above-mentioned data is usually managed by different entities, vehicle data by rail undertakings and track data by infrastructure managers. This remains a challenge to the industry and is being addressed in other studies.

Another issue posed to the railway sector is the scarce measurement of rail profiles on most networks which implies the so called ‘track-conicity’ is virtually unknown. This aggravates the problem of setting targets for the conditions of equivalent conicity in which railway vehicles can be proved to run stable at their maximum speed, as no insight is available into the values they experience in service. Therefore, while determining equivalent conicity of wheelsets on a theoretical track has long been a state-of-art procedure, determining the in-service value of equivalent conicity still poses a challenge and requires more track data to be integrated to vehicle data.

5. Safety concerns that may arise due to hunting problem- Derailment

Rail vehicle derailment is the utmost safety concern of the railways as it may cause significant casualties and property lost. Derailment occurs when the vehicle wheels run off the rails which provide the support and guidance. The reason for wheels running off rails can be very complicated and dependent on various factors. The type of derailment also varies dependent on the factors that cause the derailment, but the final result is wheels falling between rails. Therefore, any conditions that may reduce the lateral guidance provided by the rail increases the risk of derailment. As seen in the previous chapter, hunting of a rail vehicle over its critical speed causes lateral instability and thus increases the risk of derailment. Derailments discussed in this chapter relate only to the cause of losing lateral constraint at wheel and rail interface as a result of hunting. Derailments due to other causes, such as component failure, are not considered.

Derailment has always been one of the major concerns for railway operations since the first day of wheels running on rails. The essential feature of wheels running on rails creates a unique challenge for railways to ensure that wheels stay on the rail. The current trend of increase in train speed poses more challenge on the sector to address vehicle lateral guidance for high-speed operation.

Despite the advancement of railway technologies in recent years and enhancement of safety levels in comparison with the early days and also compared with other transport modes. Derailments however, unfortunately, still frequently occur.

In a study of derailments caused by hollow wheels (Harry, T. et. al, 2004), it was revealed that that 8862 reportable derailment incidents occurred between 1998 and 2000. From a review of over 300 derailment incidence cause codes defined by the Federal Railroad Administration (FRA), 53 cause codes were identified as being likely to be influenced by poor wheel – rail interactions.By further searching the FRA derailment database, 1796 derailments were found relevant to these 53 cause codes between 1998 and 2000.

Table 5 shows the distribution of the 1796 incidents.

Distribution of the Researched Incidents

Year	Total Reportable Incidents	Incidents (53 codes)	Wide Gauge	Track Alignment	Hunting	Worn Tread and Flange	Others
2000	3193	673	295	46	7	13	312
1999	2924	612	234	52	6	18	302
1998	2745	511	189	54	3	6	259
Sum	8872	1796	718	152	16	37	873

Table 5: Derailment incidents (adapted from Federal Railroad Administration (FRA) report 1998 – 2000)

In the table above, derailment incidents directly related to poor wheel – rail interaction i.e, wide gauge, track alignment, bogie hunting, and wheels with worn tread and flanges were given special attention. It can be seen also from the Table 5, that these four cause types are responsible for about 50% of derailments related to the 53 incidence cause codes.

In another study done by DNV for the European Railway Agency on freight train derailments, DNV reported causes of derailment as follows:

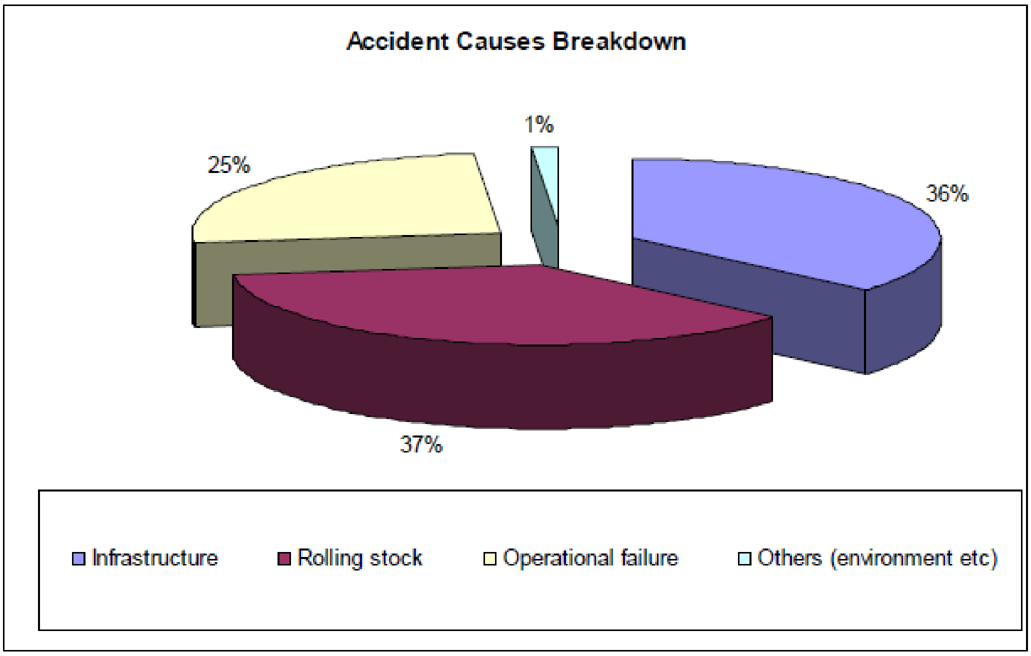


Figure 33:Approximate breakdown of freight train derailments by category [51]

Which they further provided a breakdown by category as follows:

i) Infrastructure failures leading to freight train derailments.

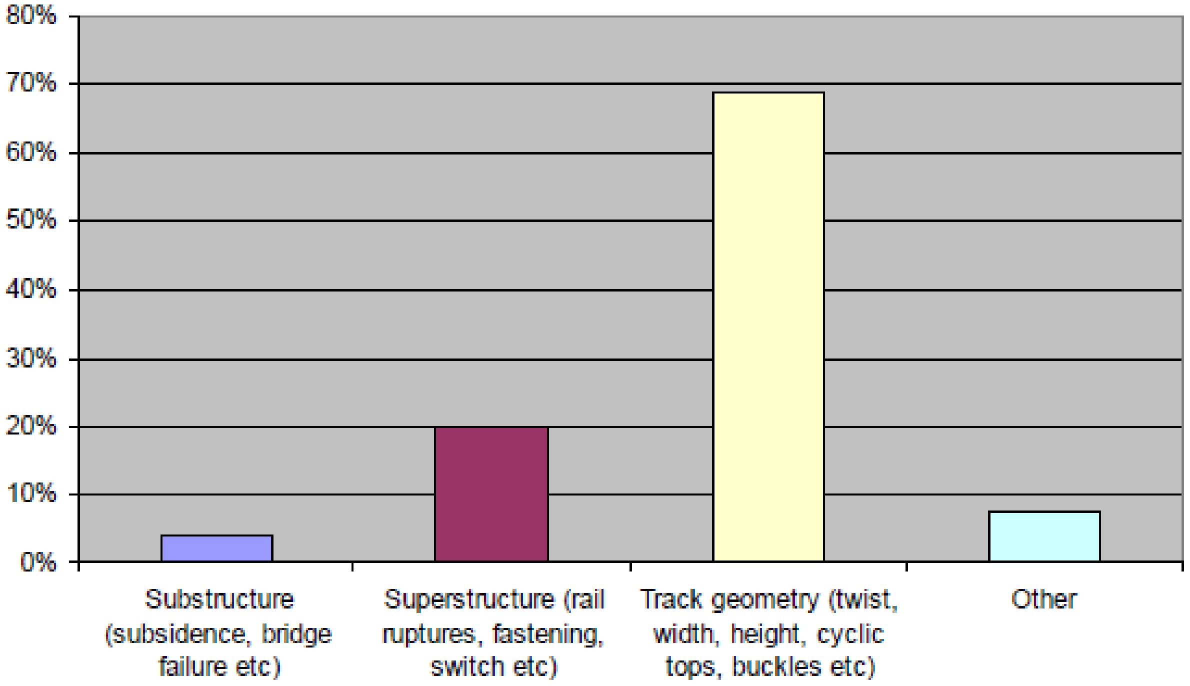


Figure 34: Infrastructure failures leading to freight train derailments [51]

ii) Rolling stock failures leading to freight derailment

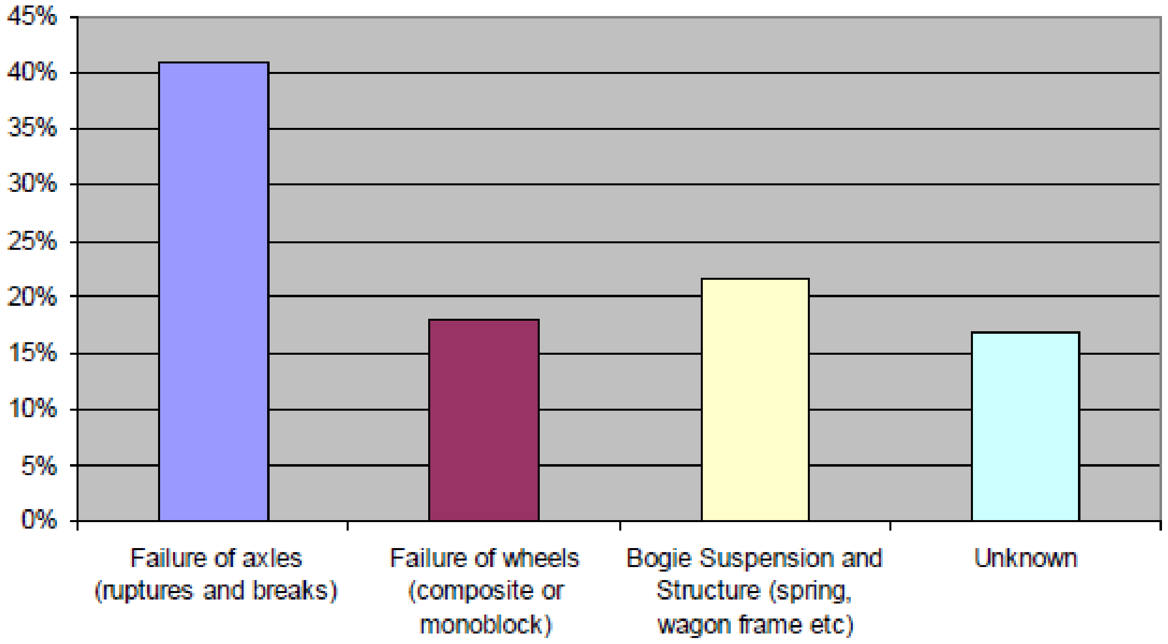


Figure 35: Rolling stock failures leading to freight train derailments [51]

iii) Operational failures leading to freight train derailments.

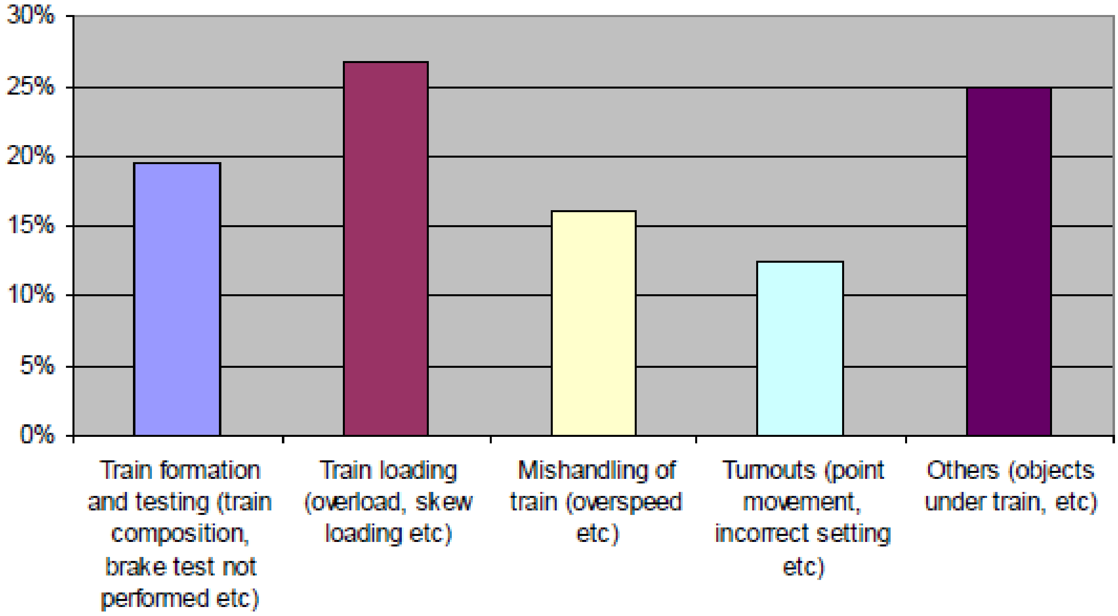


Figure 36: Operational failures leading to freight train derailments [51]

It can be seen from the results depicted in Figure33, derailments of freight trains reported is mainly due to rolling stock (37% of total accidents reported) and rail infrastructure (36% of total accidents reported) issues. The percentage of incidents caused by these two major causes of derailment are almost equivalent. Operational failures also cause a notable amount of derailment incidents for freight trains (25% of total accidents reported).

Infrastructure related failures are mainly due to track geometry irregularities and superstructure defects (Figure 34), while rolling stock failures that lead to derailment are almost all highly related to the running gear of the vehicle (bogie and its suspensions, wheels, and axles), Figure 35.

It can be confidently deduced that where the rolling stock meets the infrastructure (wheel-rail interface) is the most critical point of interaction leading to derailment.

5.1. Derailment as a result of vehicle lateral instability

As has been repeatedly addressed in this study, on tangent (straight) track, the rail vehicle wheelset generally oscillates around the track centre. The coned shape of the wheel tread is responsible for this self-centering capability of the wheelset in speeds below the vehicle's critical speed. As speed is increased, if the wheelset equivalent conicity is high, the lateral movement of wheelset, as well as the associated bogie and car body motion, can cause hunting. The contact of the wheel flanges with the rail is the only mechanism limiting hunting. Hunting as seen in the previous chapter can produce high lateral forces to damage track and to cause derailments.

Railway derailments may be classified based on the ways that wheel – rail lateral constraints are lost. Truck hunting by itself has an insignificant effect on derailment. However, excessive hunting at high speeds if faced with a severe track geometry irregularity could lead to the below types of derailment mechanisms:

i) wheel flange climb

ii) gauge widening

5.1.1. Wheel flange climb

This type of derailment occurs when wheels climb on top of the railhead then further run over the rail. Wheel climb derailments generally occur in situations where the wheel experiences a high lateral force combined with circumstances where the vertical force is reduced on the flanging wheel. It is mostly common on curves but can occur also on tangent track when the lateral force to vertical force ratio (L/V) is high.

Lateral force to vertical force ratio (L/V) is influenced by:

- Curve radius
- Wheel – rail profiles
- Bogie suspension characteristics
- Vehicle speed

These factors combine to generate a base wheelset angle of attack (AOA), as illustrated in Figure 37, which is highly relevant in curves. For what concerns this study, motion on tangent track the factors that come to play are wheel-rail profiles, bogie suspension characteristics and vehicle speed. A significantly misaligned bogie is likely to induce higher wheelset angle of attack.

Wheel climb derailments occurring on tangent track are mainly due to severe track irregularities and critical vehicle lateral dynamic motion such as bogie/truck hunting.

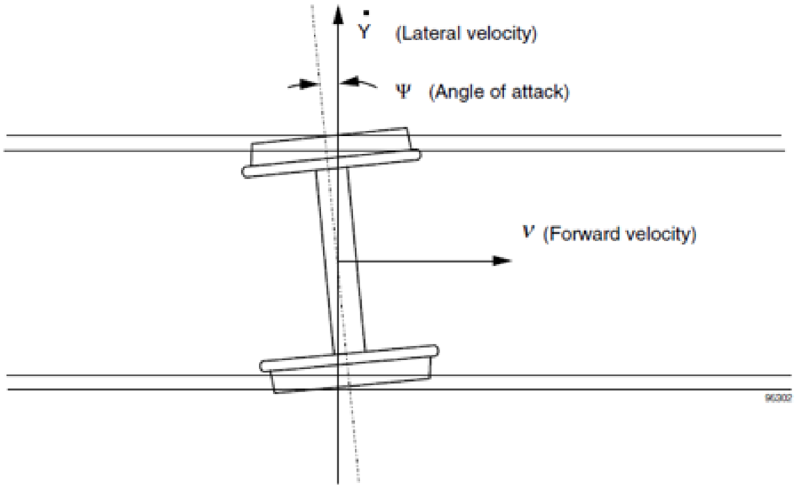


Figure 37: Wheelset angle of attack

This derailment mechanism of wheel flange climb has been investigated for several years and measures to mitigate it and safety criteria have been formulated. Among the most popular safety criteria against wheel flange climb derailment is the Nadal single-wheel L/V limit criterion. In his proposal for the French railways, Nadal established the original formulation for limiting the L/V ratio so as to minimize the risk of derailment.

Nadal assumed that the wheel was initially in two-point contact with the flange point leading the tread point. He concluded that the wheel material at flange contact point was moving downwards relative to the rail material, due to the wheel rolling about the tread contact. He further theorized that wheel climb occurs when the downward motion ceases with the friction saturated at the contact point.

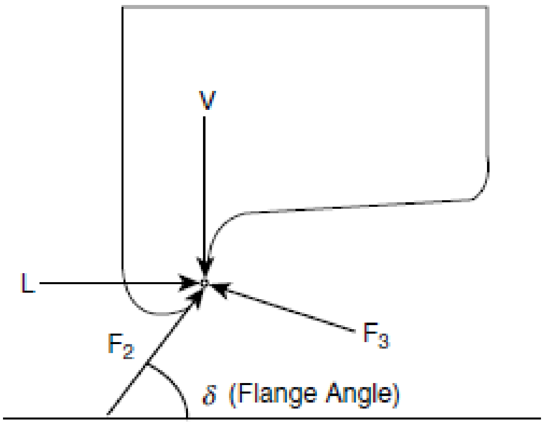


Figure 38: Nadal's single-wheel L/V limit criterion for derailment – forces at flange contact location

Based on this assumption and a simple equilibrium of the forces between a wheel and rail at the single point of flange contact, as illustrated in Figure 38, Nadal expressed the limit L/V ratio as follows:

$$\frac{L}{V} = \frac{\tan\delta - \frac{F_2}{F_3}}{1 + \frac{F_2}{F_3}\tan\delta}$$

Equation 3: Nadal's equation for limit L/V against derailment

Which in the case of saturated condition ($\frac{F_2}{F_3} = \mu$) simplifies to:

$$\frac{L}{V} = \frac{\tan\delta - \mu}{1 + \mu\tan\delta}$$

Equation 4: Nadal's equation for limit L/V against derailment (saturated condition)

For the purposes of this study, further analysis on Nadal's finding and criterion for derailment are not addressed. However, to synthesize the meaning of his work in relevance to what is addressed in this study on derailment, it can be stated that if the maximum contact angle is used, Nadal's equation gives the minimum L/V ratio at which flange climb derailment may occur, for the given contact angle and friction coefficient (μ) . in other words, below this L/V value, flange climb cannot occur. Furthermore, Nadal's work assumes flange-climbing derailment is instantaneous once the L/V limit has been exceeded. Both field tests and simulations have proved that wheel flange climb derailments would only occur when the L/V ratio limit has been exceeded for a certain distance limit or time duration limit.

5.2. Gauge widening

The combination of wide gauges and large lateral rail deflections (rail roll) are the root causes of the gauge widening derailment mechanism, (Figure 39). Again, this mechanism is more often observed in curves than straight track. Large lateral forces from the wheels act to spread the rails in curves. Both rails may experience significant lateral translation and/or railhead roll, which often cause the non-flanging wheel to drop between rails.

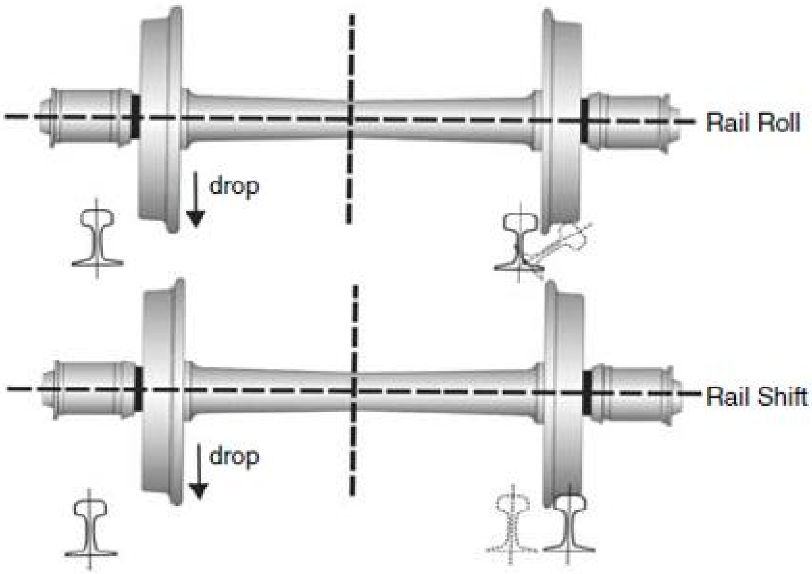


Figure 39: Derailment – Gauge widening (adapted from Blader F.B, 1990)

The key factor in this derailment mechanism as was in the wheel flange climb is the wheelsets angle of attack. High angles of attack result in large lateral forces exerted on the rails. On both curve and straight tracks, high angle of attack may be experienced by wheelsets in the presence of poor steering of the bogie/truck. The poor steering can be caused by inadequate suspensions (generally indicated by low warp or skew stiffness), high bogie turning resistance, misaligned axles, poor wheel and rail profile compatibilities, [31] and wheels having significant tread hollowing. Rail gauge wear also causes for gauge widening derailment.

Gauge widening criterion is related to the wheel and rail geometries and their relative positions as illustrated in Figure 40.

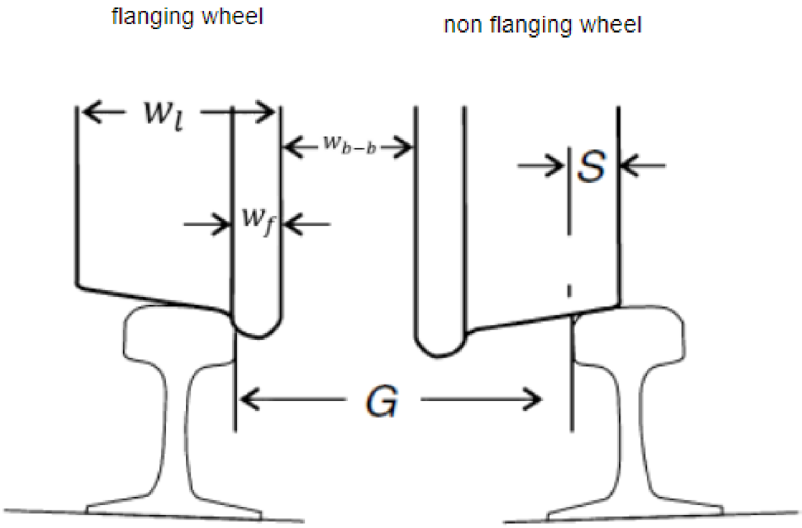


Figure 40: Gauge widening derailment criterion – based on wheel and rail geomety.

From the figure above, a criterion for defining the gauge widening derailment condition may be defined based on the wheel-rail geometry parameters as follows:

$$G \geq w_{b-b} + w_l + w_f$$

Where:

G	Rail gauge (mm)
w_{b-b}	Wheel back-to-back (mm)
w_l	Wheel width (mm)
w_f	Wheel flange thickness (mm)

A safety margin (S) can be deduced as the minimum overlap of wheel and rail required on the non-flanging wheel when the flanging wheel contacts the gauge face of the rail. In this circumstance, the instantaneous flangeway clearance on the flanging wheel is zero.

$$(w_{b-b} + w_l + w_f) - G > S$$

6. Maintenance concerns that may arise due to hunting problem–rail RCF defects

Hunting produces high lateral forces that in the long run damage the track. When vehicle hunting is onset, the displacements of wheelset are generally large, alternatively flanging from one side of the rails to the other. This contact of the wheel flanges with the rail is the only mechanism that limits hunting. In the long run the continuous contact of wheel flange with the rails causes defects such as the RCF defects at the wheel-rail interface.

Furthermore, bogie characteristics such as stiffness of suspension also influence RCF defect formation. A bogie with stiff plan view suspension resists displacement of the wheelset with respect to the bogie frame. The more flexible the suspension, the greater the potential for favourable steering moments to reduce the yaw angle in curves and thereby reduce RCF. However, a more flexible bogie/truck has a greater ability to respond to unfavourable steering moments and increase the yaw angle [32], especially in the case of bogies that have been poorly maintained.

Various studies have been done around the world to quantify the benefits of improved bogies with respect to RCF. A study in Brazil based on freight vehicles [35] found that a frame-braced bogie should theoretically halve tractions in intermediate (873 m radius) curves and reduce wear number values to below the damage threshold level required to initiate RCF. The field service results showed that tread and flange wear were 30–50 percent lower for frame braced bogies compared with standard bogies, while nearly 60 percent of test wheels on standard bogies showed RCF damage compared with only 3.5 percent for the frame braced bogie over the same 85,000-mile (136,000 km) interval. The net effect on wheel life is projected to be a four-fold increase [65].

6.1. Rolling Contact Fatigue (RCF) Defects

Rolling contact fatigue (RCF) defects are a range of defects that form and develop due to the combination of contact stress, tangential creep forces and creepage in the wheel/rail contact patch. RCF has emerged as a governing reason for rail replacement and maintenance and for rail failure and safety concerns. Since the mid-1990s especially, much research has been undertaken on all continents to understand the fundamental causes of RCF, approaches to modelling, and development of maintenance approaches.

6.1.1. Factors influencing development of RCF in rails.

The development of rolling contact fatigue in rails depends on the interplay between crack growth, which is governed by the contact stress and the tangential force at the contact patch, and wear which depends on the tangential force (again) and the creepage at the contact patch.

These parameters are dependent on many inter-dependent factors, in particular:

- Vehicle Configuration – wheelbase, axleload, wheel diameter
- Suspension Design – in particular primary yaw stiffness
- Wheel Profiles – nominal profile and state of wear
- Rail Profiles – nominal profile and state of wear
- Wheel/rail Friction
- Curve Radius
- Cant Deficiency (depends on speed, radius and cant)
- Traction and Braking Forces
- Track Geometric Quality
- Wheel and rail material properties

The large number of variables makes the analysis of the big picture a massive undertaking. During the investigation of RCF for Railtrack (now Network rail Infrastructure Limited), well over 2000 separate cases were simulated then, and work is continuing to fill in gaps in the jigsaw (Evans J, Iwnicki S.D, 2002).

In this study we limit our focus to RCF due to the hunting phenomena. Therefore, parameters such as curve radius are not addressed as the bogie instability is restricted to conditions on tangent track.

6.1.2. Types of Rail RCF defects

Defects which occur due to rolling contact fatigue can be divided into subsurface initiated and surface-initiated cracks. Subsurface cracks are often caused by metallurgical defects. On the other hand, surface-initiated cracks are formed mostly due to increase in traffic density and axle load (Olofsson and Nilsson, 2002). In this study focus is confined to RCF defects initiated at the rail surface, subsurface initiated defects due to metallurgical deformities are out of scope.

6.1.2.1. Rail Gauge corner cracking

This is a surface condition that occurs mainly on the high rails in sharper curves. This RCF type of defects entail thin cracks appearing at the gauge corner of the rail (Figure 41).

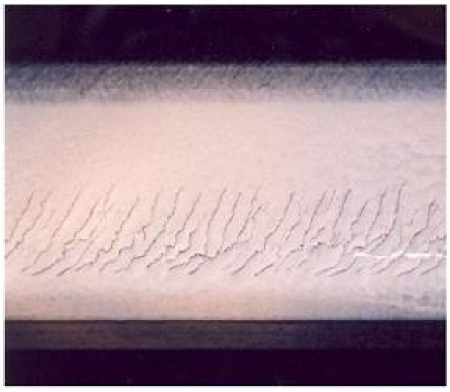


Figure 41: Rail gauge corner cracking

Rail gauge corner cracking develops as a result of high wheel-rail contact stresses coupled with sufficiently large shear stresses because of slip between the wheel and rail. Gauge corner cracking (GCC) is often regularly spaced and may occur for long lengths of track (e.g., the entire curve) or may be found in clusters. In the latter case, it is usually associated with track geometry perturbations.

6.1.2.2. Shelling

Shelling is a defect caused by loss of material initiated by subsurface fatigue (Nielsen and Stensson, 1999). Shelling normally takes place at the gauge corner of high rails in curves. In this type of RCF defect, an elliptical shell-like crack propagates in the subsurface parallel to the rail surface. When these cracks emerge on the surface, they cause the metal to come out from the crack area. Sometimes these cracks move in downward direction also, this may probably lead to a transverse fracture of rail.

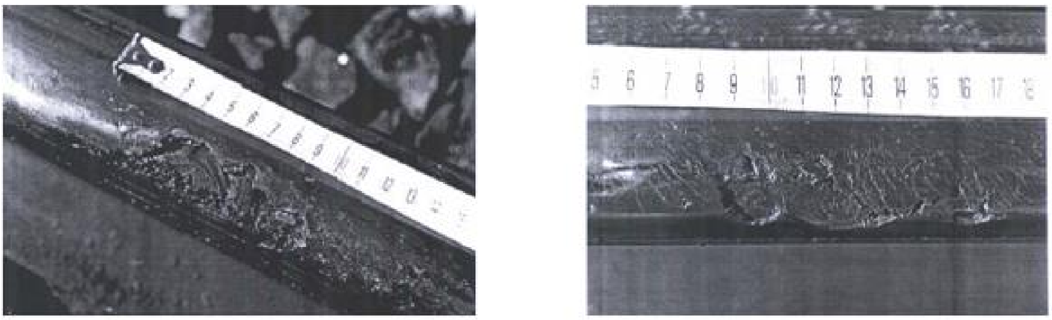


Figure 42: Shelling in rails (adapted from Mats Rhen and Dan Larsson, LTU)

6.1.2.3. Squats

The squat is a surface defect most commonly associated with high-speed rail and areas of high tractive effort. It is characterized as a shallow depression more or less in the center of the rail head on tangent and mildly curved track. This depression is a result of crack which grows progressively and branches out horizontally just below the running surface, detaching it from the rail body.

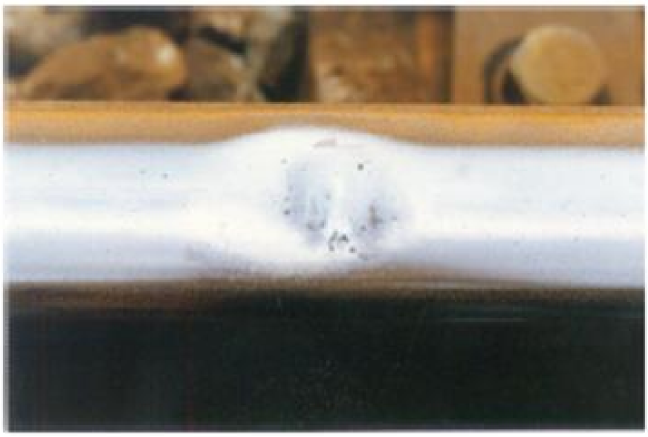


Figure 43: Rail squat

Squats appear in crown area of straight rail sections. They are surface initiated defects formed by RCF. A squat is formed by two cracks, a leading crack and a trailing crack. Both these cracks propagate in opposite direction. The leading crack proceeds in traffic direction, but the trailing crack propagates faster than the leading one [56].

6.1.3. Economic repercussions of RCF

In North America where studies have been performed regarding RCF defcets on rails and their economic implication, it was evidenced that 15–22 percent of all rail replacement is due to surface and subsurface-initiated defects [39]. Magel (2011) states that the replacement of rail represents a large capital expense for any railroad, ranging from about USD375,000 per track-mile on a conventional freight railroad to USD2 million on underground mass-transit lines.

Grassie, S.L (2005) states that the cost of RCF defects to the European rail system was estimated in 2000 to be roughly €300 million (USD417 million) annually but following the Hatfield derailment and increased recognition of RCF in Europe, that number has certainly risen.

Extra penalty payments to train operators after the Hatfield derailment and replacement costs of switches or crossings in which gauge corner cracks were found amounted to £561 million in the period 2000–2001, this in the UK alone [43]. In 2004, the annual cost of RCF to network rail alone was estimated as being at least £200 million and included RCF cracking of wheels [40].

In the USA, Federal Railroad Administration (FRA) reports on costs in 2005, it surfaced that RCF would account for approximately 105 derailments and USD30 million, along with 7 nonfatal casualties. On the mechanical side, 22 accidents as a result of broken wheel flanges and broken rims amounted to nearly USD11 million in FRA costs in the same year [65].

The annual cost of rail inspections for defects is not known, but although not all defects are due to RCF (other causes include broken welds, base plate cracks, etc.), there is no doubt that a considerable fraction of the cost can be attributed to the problem. In the European Union, the cost of rail defects, a large percentage of which are initiated by RCF, has been estimated at €2 billion per year and, on this basis, became the UIC‘s first World Joint Research Project [39].

7. Track Maintenance

7.1. Maintenance definition

Literature provides various definitions of maintenance. From the European standard EN 13306:2010 ‘Maintenance – Maintenance Terminology’, one settles for the definition of maintenance as “combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function”. Therefore, the primary aim of maintenance is to prolong the state of functioning of equipment or a system by not allowing it to deteriorate in condition.

Railways require maintenance to ensure an acceptable level of operating conditions. In 2018, railway maintenance expenditure in the European Union (EU27) was estimated at 20,6 billion Euros, accounting for more than half of the total rail infrastructure expenditure [12]. Furthermore, railways are amongst the longest-lasting and most capital-intensive assets, and even minor improvements in maintenance cost and efficiency can have significant effects on the total life cycle costs. Therefore, a maintenance management system is necessary to ensure the infrastructure system's availability.

7.2. Maintenance strategies

A maintenance strategy used can either be preventive or corrective, Figure 44. Preventive maintenance tasks are often referred to proactive strategies while corrective maintenance referred to as reactive strategies.

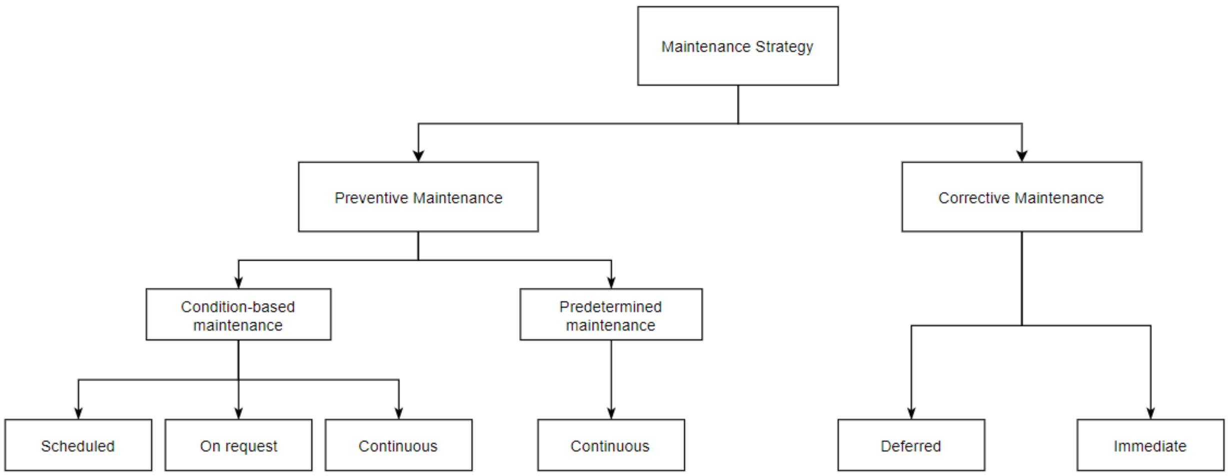


Figure 44: Maintenance strategy

As the names suggest, preventive maintenance is conducted “before a detected fault” while corrective maintenance is performed “after a detected fault”.

In a more formal definition (EN 50126)

- Preventive Maintenance: The maintenance carried out at pre-determined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item [55].
- Corrective Maintenance: The maintenance carried out after fault recognition and intended to put a product into a state in which it can perform a required function.

Preventive maintenance is divided into condition-based and predetermined maintenance. Condition based maintenance includes a combination of monitoring and/or inspections and/or testing, analysis, and the ensuing actions. Predetermined maintenance as the name suggests is carried out at predetermined intervals (time or tonnage based) according to prescribed criteria by the infrastructure manager. It is intended to reduce the probability of failure or degradation of an item’s functioning.

Today, there is vast pressure to shift from reactive maintenance strategies to proactive maintenance strategies such as condition-based maintenance and predictive maintenance especially in situations where infrastructure is old and more capacity is demanded.

Condition-based maintenance (CBM) is foreseen to be an attractive lever for increasing maintenance efficiency. With efficiency gains of 10 to 15% expected, industry experts estimate that the global maintenance market can save up to approximately EUR 7.5 billion per year by moving towards condition-based maintenance [61]. Condition-based maintenance (CBM) is characterized by application of sensor technology, automation and data analytics that sees diagnostics conducted continuously in real-time or quasi real time as the rail assets – trains and infrastructure are in operation. Failure data collected in the past helps identify a critical parameter threshold where an equipment or component should be scheduled for maintenance to avoid failure. In this way maintenance personnel are presented with an agile approach to work as they know a priori exactly which equipment or component may require intervention, where it is located, which spare parts are required and allocated maintenance window to carry out the intervention.

Predictive maintenance on the other hand requires monitoring of not only the condition of equipment and components themselves but also the condition of factors influencing them. On top of this additional data sources need to be tapped into and managed. Industry experts hold that, the additional jump from a condition-based towards a predictive maintenance scheme would require further effort and additional investment. According to McKinsey study on the rail sector's changing maintenance game (2017), the maximum additional savings on maintenance costs due to the jump towards predictive maintenance is estimated at 10%, not significant enough yet and to be aggressively pursued.

7.3. Maintenance Management

Infrastructure managers try to ensure the successful management of costs and quality, and the relation between the two. This is essential because the train operators as well as the passengers are imposing ever increasing quality requirements on the rail infrastructure. Therefore, the infrastructure managers require the best infrastructure quality at the lowest cost. The way to achieve this objective is through proper maintenance management.

Esveld (2001) gave examples of the type of data required for a Track Maintenance Management System (TMMS), as listed below:

- Measurements
- Planning
- Infrastructure
- Inspections
- Work carried out
- Costs

However, difficulties in the accurate anticipation of maintenance prevent extremely precise maintenance planning and management. Besides, the amount of funding allocated for maintenance work is often regarded as a compromise, as too much according to top management, and too little according to the operating and maintenance staff.

Consequently, the selection of the optimal maintenance strategy can be challenging. A systematic approach for the determination of the deterioration of track components is necessary to gauge fully the status of the track system and components. This will require proper track condition assessments, the establishment of a standard condition rating system, and the development and regular updating of prediction models for various track components.

An effective infrastructure maintenance management system requires RAMS management and life cycle cost (LCC) management to be thoroughly integrated into the asset management of the system.

7.3.1. RAMS and LCC approach to track maintenance management

Due to the long lifetime of the track and track components, pre-installation technical and economic assessments are necessary to optimize the track construction and obtain the return on investment (ROI) in a manageable timeframe. RAMS and LCC techniques are two acknowledged methods for assisting the optimization process. In the past decade, RAMS and LCC analyses in the railway sector have attracted much more attention than before which has been demonstrated by many research reports and has led to the development of commercial applications [66].

7.3.1.1. RAMS

Traditionally maintenance decisions for the railway infrastructure have been based on past experience and expert estimations. The application of RAMS (Reliability, Availability, Maintainability and Safety) analysis for railway infrastructure maintenance management is still limited but attracting new interest of infrastructure managers for today's operations.

The European standard (EN50126) first published in 1999 by CENELEC defines RAMS from the railway applications' context. The standard defines RAMS – Reliability, Availability, Maintainability and Safety as a characteristic of a system's long term operation that is achieved by the application of established engineering concepts, methods, tools and techniques throughout the life cycle of the system.

RAMS elements are defined in the EN50126 as:

- *Reliability*: the probability that an item can perform a required function under given conditions for a given time interval.
- *Availability*: the ability of a product to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided.

- *Maintainability*: the probability that a given active maintenance action, for an item under given conditions of use, can be carried out within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources.
- *Safety*: the state of technical system freedom from unacceptable risk of harm

Inter-relation of railway RAMS elements is illustrated in the figure below:

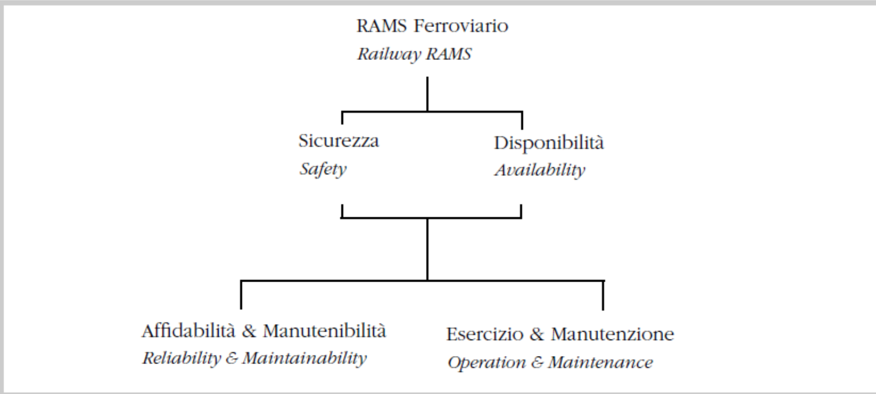


Figure 45: Inter-relation of railway RAMS elements (CEI EN 50126: 2000-03)

Factors that influence the railway RAMS are identified and described in the EN50126. The standard states that:

> *'The RAMS of a railway system is influenced in three ways, by sources of failure introduced internally within the system at any phase of the system lifecycle (system conditions), by sources of failure imposed on the system during operation (operating conditions) and by sources of failure imposed on the system during maintenance activities (maintenance conditions). These sources of failure can interact.'*

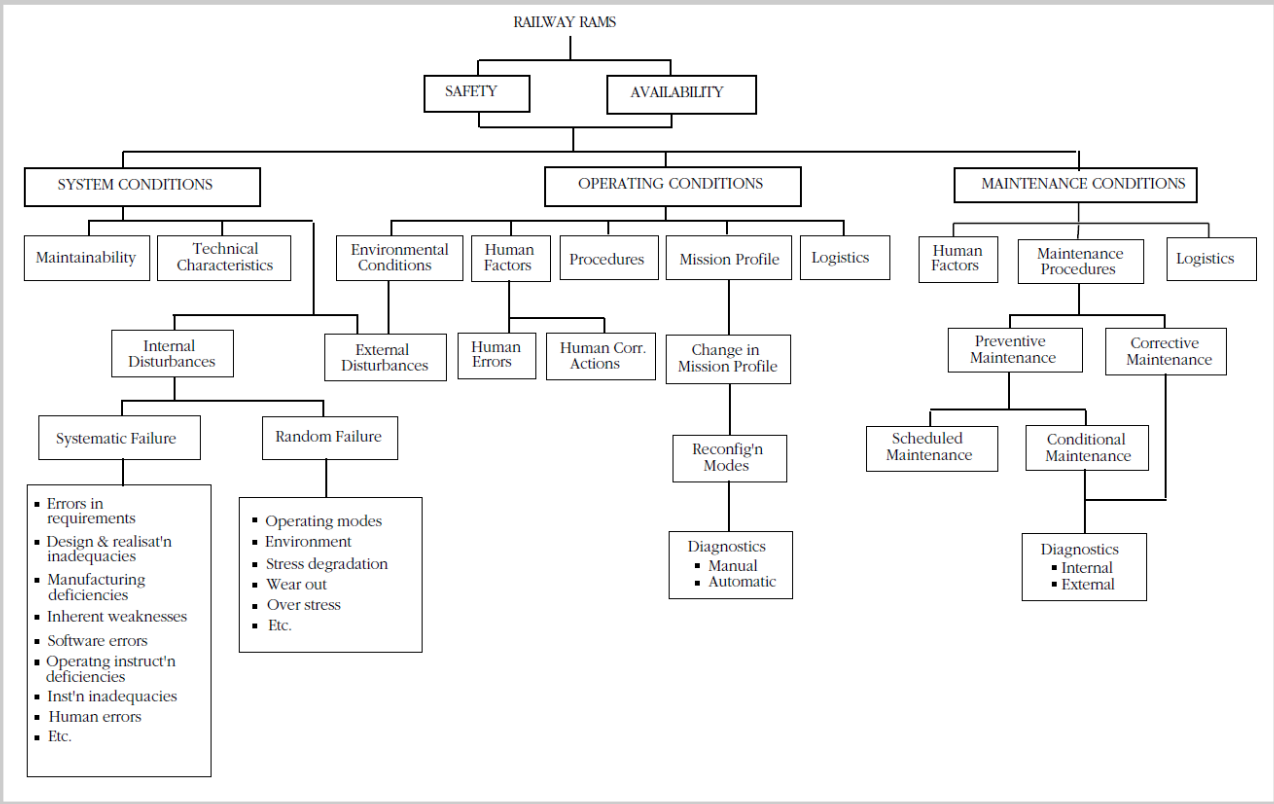


Figure 46: Factors influencing railway RAMS (adapted from EN 50126, 1999)

To achieve a dependable track system, the factors specifically affecting the track RAMS need to be identified. The table below identifies the specific factors that affect the track RAMS, (Patra, 2009).

	Physical parameters	Technical parameters
System conditions	Track curvature (transient curve in, transient curve out, radius)	Quasi-static stress
	Track gradients (start, end, value)	Quasi-static stress
	Rail (rail type, jointed or welded)	Yield strength (Young's modulus)
	Ballast (ballast type, ballast size)	Stiffness, Damping
	Sleeper (sleeper type, sleeper spacing)	Stiffness, Damping, Bending stress
	Fastener (fastener type)	Damping
	Subgrade (geological condition)	Stiffness, Damping
Operating conditions	Track operating conditions:	
	Loads (annual MGT, maximum axle load)	Bending stress, Shear stress, Contact stress
	Environment (temperature)	Thermal stress
	Vehicle operating conditions:	
	Speed of trains	Vertical stress, Lateral stress
	Vehicle condition (hollow wheels)	Dynamic stress
Maintenance conditions	Grinding	Wear rate
	Tamping	Change in track stiffness
	Lubrication	Change in friction co-efficient
	Renewal of track components	Interval of renewal
	Corrective replacements of track components	Failure rate of track components

Table 6: Factors affecting track RAMS (Patra, 2009)

RAMS analysis for the track is based on the following elements:

- RAMS database
- Failure modes
- Methods and tools for the RAMS analysis

The utilization of failure and maintenance data is an important factor in RAMS analysis and the management of the track system. Traffic and track geometry databases should be considered along with the failure and maintenance databases.

FMECA, Markov analysis and Reliability Centered Maintenance (RCM) are all common concepts and analytical tools utilized in RAMS analysis, especially in the operation and maintenance phase of a railway system.

The figure below depicts typical RAMS process in the operation and maintenance phase.

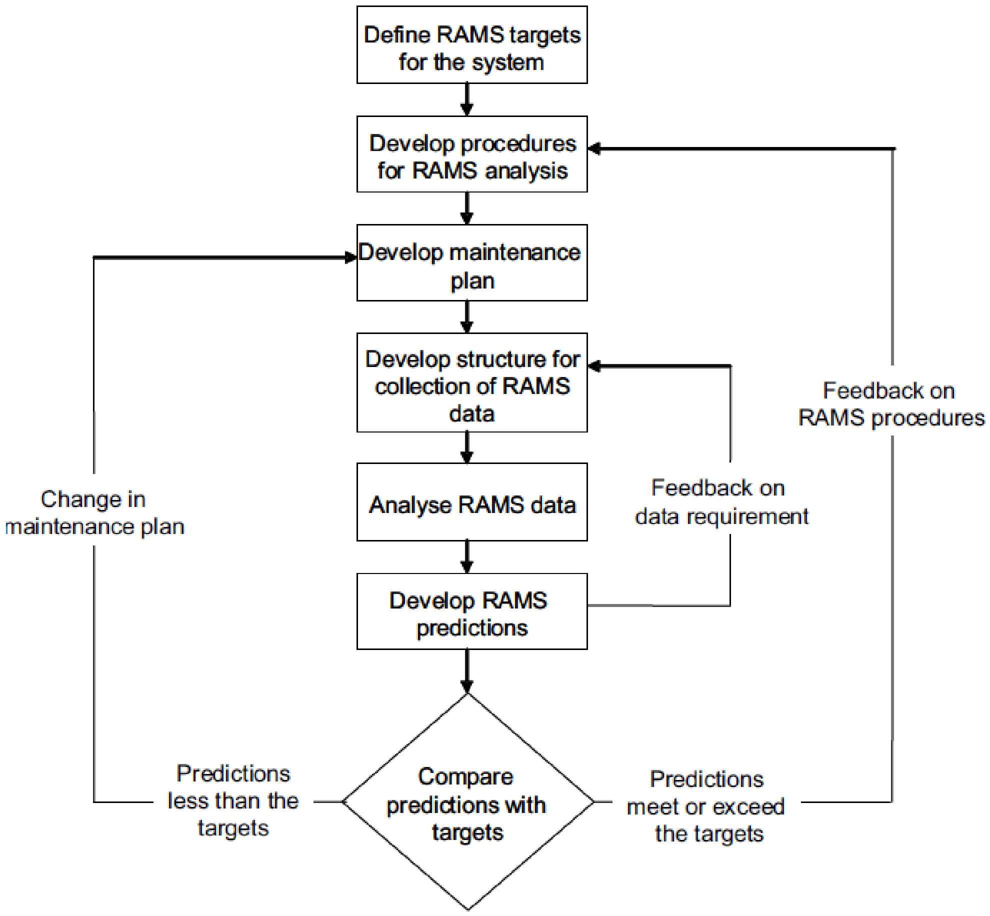


Figure 47: RAMS process operation and maintenance phase

7.3.1.2. LCC

Infrastructure maintenance policy and budget constraints play a fundamental role in selecting a maintenance strategy. Life cycle cost (LCC) analysis is a tool to determine the most cost-effective option among different competing alternatives to purchase, own, operate, maintain, and finally dispose an object or process, when each is equally appropriate to be implemented on technical grounds. A maintenance strategy with the lowest LCC is considered as the cost-effective solution to be implemented in the infrastructure operations.

Putallaz (2003) identifies three parameters that influence the performance of the track infrastructure as:

- **Capacity** - expressed in terms of usable train paths during a certain time span.
- **Substance** – expressed as the average remaining useful lifetime of the track's components.
- **Quality** – expressed as the quality of track's geometry and components.

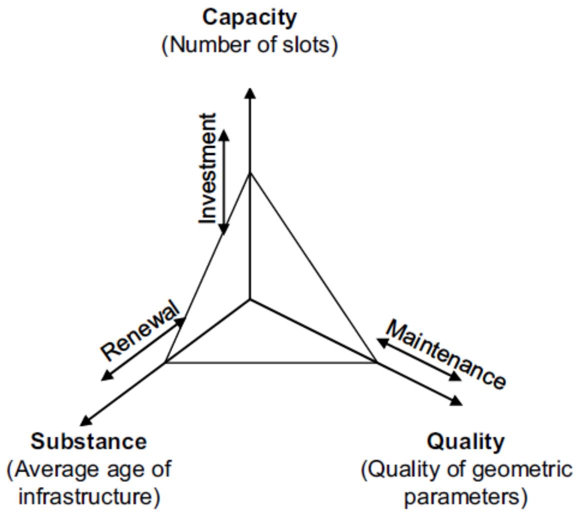


Figure 48: Basic parameters of railway infrastructure influencing performance (Putallaz, 2003)

Infrastructure management boils down to setting these three parameters at their most appropriate level so as to maximize efficiency. The three performance parameters cannot be adjusted independently as they are not mutually exclusive. For instance, an old infrastructure (low substance) requires more maintenance (to increase the quality), whereas a bad geometry (low quality) increases the wear on the infrastructure (lower substance). Similarly, more engineering works (maintenance & renewal) require more track possessions (less capacity), while more traffic (high capacity) induces more wear of the infrastructure [66].

Adjustments may be made to the capacity through the investment policy, to the infrastructure substance through the renewal policy, and to the quality through the maintenance policy, (Figure 48). In adjusting these parameters, the cost aspect of each activity is to be considered, and this is where the LCC analysis comes to play. Life cycle costs can be used as a tool to take cost-effective decisions on investment, renewal and maintenance, in order to adjust the three mentioned parameters to optimize the infrastructure performance.

Research on railway infrastructure maintenance decision supporting models based on the RAMS and LCC techniques are underway. The main goal is to optimize maintenance through a holistic approach with the life cycle of the infrastructure at the center stage.

Patra (2009) addresses the high potential of both RAMS and LCC as analytical tools for estimating the track system and cost effectiveness of the track assets, as well as for taking effective decisions on the maintenance of track assets. The close relation between asset maintenance and asset is clear to see as effective maintenance increases the asset performance, while asset performance acts as a decision tool for asset maintenance.

The figure below illustrates the relationship between maintenance management, asset performance and asset maintenance, (Patra, 2009).

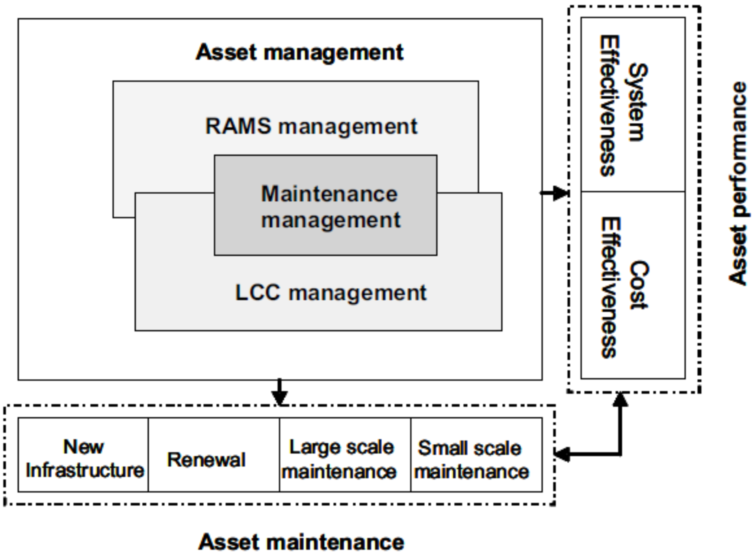


Figure 49: Factors influencing maintenance management (adapted from Swier and Luiten, 2003)

7.4. Track Maintenance Planning

Decisions related to rail infrastructure maintenance are taken in order to keep a balance between economic and safety aspects. The goal is to find the effective maintenance procedure to optimize the track possession period and the train speed restriction regime and ultimately increase the track availability.

The different components of the railway asset are structurally and economically interdependent. Scale effects are involved in their maintenance and renewal, while their degradation is often structurally related. As operations have to be continued on the rail network and budgets are often restricted, all kinds of constraints have to be considered in the planning of infrastructure maintenance.

The concepts of the maintenance planning process are developed in the following steps (Zoeteman, 2006):

- Generation of maintenance strategies for individual assets (e.g. corrective or preventive, time based or condition based, strategies are distinguished based on the criticality of the individual asset for the entire production system)
- Definition of clustering rules, which optimize the frequencies of activities on the basis of scale or scope effects.
- Definition of rules for assigning time windows to maintain packages on the basis of opportunities that occur in the middle or short term.

Track quality measures and track deterioration models are highlighted as key areas for a structured planning process to be established.

Zarembski (1998) described three tools which railway organizations could use to improve the efficiency of maintenance operations (Figure 50) automated inspection systems, databases and maintenance planning systems.

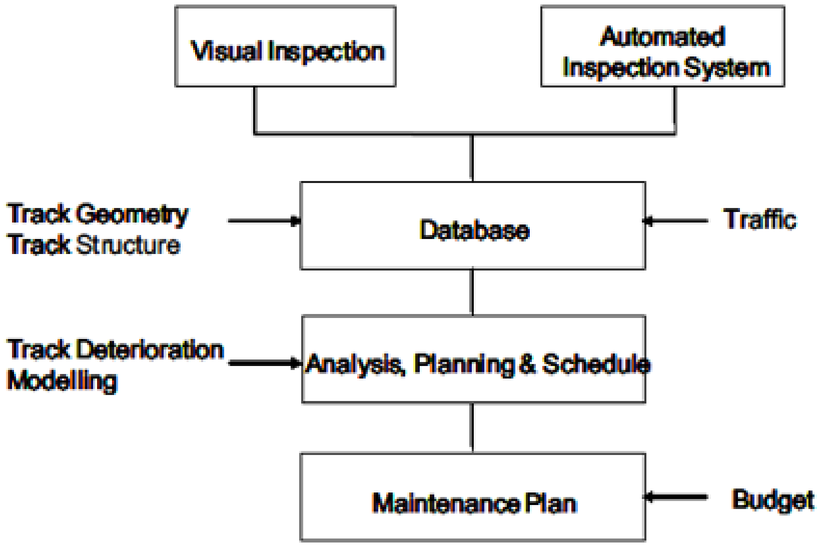


Figure 50: Overview of track maintenance planning (adapted from Zarembski, 1998)

The lack of integration between these tools has prevented railway organizations from taking full advantage of their potential.

7.5. Maintenance actions against RCF

7.5.1. Detection and Monitoring of RCF

Nondestructive inspection is the common method of detecting and monitoring rail defects including RCF defects. Surface and sub-surface defects on the rails that might appear benign to the naked eye need to be measured through high precise rail inspection systems to ensure they do not progress to dangerous states. Management of RCF requires a technology for identifying cracks in their earlier stages of development, where they can be easily removed through rail grinding.

The most diffused technologies for rail inspection (both surface and surface) are:

i. Eddy current
ii. Ultrasonic
iii. Vision technology

7.5.1.1. Eddy Current inspection

Eddy current is a robust and relatively straight-forward inspection technology that has been successfully applied in various industries including oil pipeline, aviation and rail. The inspection approach utilized involves sensors with one exciting coil and one sensing coil. The exciting coil is fed with alternating current (AC) so as to generate a magnetic field near the surface of the rail head. Eddy currents are induced just below the surface of the rail head as a result of changes in the magnetic field. Consequently, the eddy currents generate changes in the secondary magnetic field which are detected by the search coil in the form of an induced voltage. If the inspected area is free of defects then the impedance of the eddy current sensor remains constant. However, when a near-surface or surface defect is present in the rail head, the eddy currents are disturbed causing fluctuations in the secondary magnetic field giving rise to changes in the impedance. [41]

Defects detected by this method of rail inspection are surface and near-surface defects only. This is due to the fact that eddy current can only penetrate into the skin of the target sample. From a practical consideration, the eddy current system is very sensitive to changes in the distance between the coils and the target, so a consistent standoff is required. Typically, that distance is 1–2 mm, which is difficult to achieve at high speed on rough rail and with continually varying rail head shapes [65].

7.5.1.2. Ultrasonic measurements

Ultrasonic techniques for rail inspection often cannot see surface and near-surface defects not because of limited potential but rather because the amount of noise and scatter from the near surface signal is so large and complex that the analysis systems generally ignore the signal associated with the first few millimeters of the rail surface to focus on internal inspection.

Papaelias, M. et al (2008) state that the conventional ultrasonic probes could be used to detect larger (>4 mm) surface-originated defects such as deep head checks and gauge corner cracking, although Hiensch, M., and Smulders, J. (1999) report evidence of ultrasonics being used to monitor surface crack growth. There is no doubt that information exists in the ultrasonic signal related to the condition of the rail surface, but to date, it does not appear to be a subject of active research.

The application of ultrasonics in rail inspections may be subject to obstacles that include martensitic layers at the surface of a rail for instance as a result of a wheel burn that do prevent effective ultrasonic testing of rail as well as presence of larger and more critical internal defects which may be shadowed by smaller surface cracks during inspection. For these reasons, current best practice is to combine nondestructive evaluation with preventative rail grinding to optimize the tradeoff between maintenance cost and structural reliability [41].

7.5.1.3. Vision technologies detection

Vision inspection approach based on machine vision techniques are continuously gaining popularity in the railway infrastructure maintenance context for inspection of components like joint bars, rail ties condition, and missing fasteners. However, its practical application to characterizing surface condition currently appears unclear. A 2004 study by the National Research Council of Canada (NRCC) concluded that —although high-speed laser and video systems exist for scanning and recording various track features, none appear to provide a quantitative assessment of anything but the simplest of surface defects (e.g., ballast spalls). RCF cracks are an order-of-magnitude more difficult to distinguish than spalls [46].

The table [41] below illustrates a comparison between the three common rail inspection technologies previously described.

Eddy current	Ultrasonic	Vision
Good at detecting surface defects	Poor at detecting surface defects	Can detect only surface defects
Near subsurface defects reasonable to detect	Near subsurface defects difficult to detect	Near subsurface defects cannot be detected
Deep subsurface defect detection is impossible	Good subsurface defect detection	Deep subsurface detection is impossible
Can detect through surface layers	Grease and films are problematic	Surface layers hide most flaws
Probes are less sensitive to flaw orientation	Signal is strongly influenced by flaw orientation	Detection sensitive to lighting sources
No couplant required	Couplant typically required	No couplant required
Probe can be made wide and profiled to cover wear face	Defects must be on probe centreline	Wide field of view allows full coverage of rail wear face
Faster inspection speeds	Slow inspection speeds	Fast to very fast inspection speeds possible

Table 7: Comparison of the three common detection technologies applied to rail inspection

7.5.2. Rail Grinding

Rail grinding is a maintenance strategy that had the initial purpose to eliminate rail corrugation, in order to reduce track stresses and to extend the service life of the rail. With increase in train speeds and axle loads, occurrence of rolling contact fatigue defects became more popular and rail grinding was soon adapted also to eliminate these types of rail defects so as to achieve a rail profile that optimizes wheel-rail contact and combats noise and vibration.

Conventional grinding typically involves taking an initial measurement of the rail head condition to determine what material removal is required. In most cases, the maintenance actions against RCF defects are based on the results of Non Destructing Testing (NDT) and visual inspection as previously addressed.

Hand grinding or corrective machining is applied to correct RCF defects and depending upon the severity, these must be corrected within a short time frame, and unless a track possession is planned, they must be corrected by manual interventions. For more severe rectifications of the rail, a milling machine can be used for greater material removal rate per pass with a positive impact on both LCC and track possession time [66]. Maintaining the rail profile through grinding is necessary to give the right wheel and rail contact band. Therefore, grinding is the principal maintenance action against RCF defects.

Various studies are being pursued by scholars and industry experts around the globe on optimization of grinding, in terms of frequency, number of passes and amount of material removal. A good understanding of RCF defects in the rails is key to rendering these studies and ultimately optimization of the grinding process a success.

PART II

Industrial Context - Prediction of bogie (truck) hunting and influencing wheel-rail parameters.

8. Necessity of Bogie (truck) hunting detection system for railway infrastructure

In the Det Norske Veritas (DNV) report for the European Railway Agency regarding research on assessment of freight train derailment risk reduction measures (2011), the accredited registrar identified for the Agency all prevention and mitigation measures that existed then or could be implemented within the short term (before 1st of January 2013) or medium term (ready to be applied or to be introduced in EU regulation within 5 to 10 years) [51].

In this effort, DNV consulted with industry players i.e, infrastructure managers (IMs), railway undertakings (RUs) and suppliers of technical measures in the European Union to establish:

The types of measures (technical, operational, organizational or human) they currently use to either reduce the frequency or mitigate the consequences of freight train derailments.

- The effectiveness of these measures.
- Their plans for introducing additional measures in the short term and beyond.
- Where an IM or RU had indicated the use of a technical measure, they were then asked in a subsequent round of communication for their experience of the reliability performance and effectiveness of these measures.

In the findings of DNV, the following infrastructure preventive measures were reported:

Type of measure	P#	Measures and motivation:	Where applied:	Source for Information:
Technical infrastructure	P-1	Installation of check rails to prevent derailments, in particular in sharp curves, as it will hinder flange climbing on outer rail in sharp curves. Check rails are also used in other conditions and have a wear reducing effect also. For further info see 4.3.2.1	In points in most countries. In line track with sharp curves GB and republic of South Africa.	Network Rail Track construction standard, NR/SP/TRK/102
	P-2	Installation of track and flange lubrication in front of track sections with narrow curves to reduce rail flange friction and limit the risk of flange climbing on rail with subsequent derailment consequences. For further info see 4.3.2.2. See also flange lubrication measure on rolling stock (locomotives) 4.3.5.1.	Several countries including Austria. Great Britain	Ref. [6]
	P-3	No longer used		
	P-4	No longer used		
	P-5	No longer used		
	P-6	Use of ground penetration radars (Geo radars). Ground penetration radars are used to survey conditions of track bed superstructure with regard to quality and water content. This is mainly used through ad hoc baseline runs to provide information for planning of maintenance and renewal, but permanent installations can also be considered. For further info see 4.3.2.3.	Several countries including US and Norway.	Ref. [7]
	P-7	Rolling stock mounted equipment for monitoring of rail profile conditions. For further info see 4.3.2.6.	Mermec supplied equipment	Mermec brochure [8]
Infrastructure; Control Command and Signalling	P-8	Track circuit as part of signalling system may detect rail ruptures. For further info see 4.3.2.4	Most countries	General railway knowledge
	P-9	Interlocking of points operation while track is occupied. This is not fully implemented at shunting yards. Hence a number of derailments occur due to points being operated while it is occupied by a train. This action very often causes derailment. Extend use of interlocking of remote controlled points to include tracks at shunting yards used for train movements. Interlocking of switch movement if the switched is occupied by rolling stock. For further info see 4.3.2.5	The protection measure is utilised and applied in most countries. The degree of application of point interlocking at shunting yards varies.	Several derailments reported due to shifting of point while occupied by train.
Trackside rolling stock supervision	P-10	Installation of hot axle box (hot bearing) detectors for detection of faulty and hot bearings and axle journals in order to remove them from train prior to derailment. For further info see 4.3.3.1.	Several European countries.	Questionnaire responses
Trackside installations to supervise	P-11	Installation of acoustic bearing monitoring equipment (This is partly an alternative to hot axle box detectors). The purpose of the installation is to detect faulty bearings by sound analysis and implement bearing maintenance prior to bearing seizure and hot temperature development. For further info see 4.3.3.2.	US, GB, Norway (installation plans)	Questionnaire responses & Ref [9]
Type of measure	**P#**	**Measures and motivation:**	**Where applied:**	**Source for Information:**
rolling stock	P-12	Installation of hot wheel and hot brake detectors. For further info see 4.3.3.3.	Several countries.	Network statement, Questionnaire responses
	P-13	Installation of wheel load and wheel impact load detectors. For further info see 4.3.3.4.	Several countries.	Network statement, Questionnaire responses
	P-14	Installation of dragging object and derailment detectors. For further info see 4.3.3.5.	US and other countries	Ref [9]
	P-15	Bogie performance monitoring/Bogie lateral in-stability detection (bogie hunting). For further info see 4.3.3.6.	US and other countries, including Turkey.	Ref [9]
	P-16	Wheel profile measurement system / Wheel profile monitoring unit. For further info see 4.3.3.7.	US and other countries	Ref [12]
	P-17	No longer used		
Infrastructure Operational/ organisational	P-18	Make sure available maintenance resources are sufficient in relation to network extent and traffic levels. If not possible to ensure sufficient resources a measure could be to close low traffic lines or take little used tracks out of operation. Lines and tracks where the minimum infrastructure safety requirements cannot be maintained should be closed down. For further info see 4.3.4.1	Low traffic line closure has been common in several countries.	General railway knowledge
	P-19	Ensure that the track/train clearance gauge including the flange groove is free of obstructions that can cause collisions or derailments. Special focus to flange groove in level crossings. For further info see 4.3.4.2.	Normal inspection and maintenance in most countries.	A1 final draft report reviewer
	P-20	Perform ultrasonic rail inspection of track at sufficient frequency in order to detect rail cracks before dangerous ruptures occur. This is an activity carried out by most infrastructure managers with frequencies dependent upon rail age and traffic loads. For further info see 4.3.4.3.	The activity is performed by most infrastructure managers. Frequency varies according to track loading.	General railway knowledge
	P-21	Perform track geometry measurement **of all tracks** in order to detect track sections requiring maintenance actions. Regular track geometry measurements are carried out by most infrastructure managers. The completeness of the measurements with respect to track coverage at stations as well as intervals may vary. Frequency normally dependent upon traffic load and allowable speed level of track. For further info see 4.3.4.4.	Most infrastructure managers but frequency may vary. Mixed coverage of sidetracks.	Accident investigation reports
	P-22	Establish EU-wide intervention and/or immediate action limits for track twist. The final draft TSI for CR Infrastructure specifies safety limits for track twist but intervention limits are left to the NSA or infrastructure managers of the various countries and they vary to a certain extent. Since the rolling stock are to be interoperable across all infrastructures the track intervention limits should also be corresponding. For further info see 4.3.4.5	Lack of consistency between countries, e.g. GB & Norway with regard to track twist intervention limits.	Final draft TSI CR Inf. Ref.[10] & RGS GC/RT5021 [11]
	P-23	Establish EU-wide intervention and/or immediate action limits for variation of track gauge.	Variation in maximum gauge	Final draft TSI CR Inf.
Type of measure	**P#**	**Measures and motivation:**	**Where applied:**	**Source for Information:**
		Present limits varies among infrastructure managers and the intervention limit specified in the final draft TSI for CR Infrastructure is less stringent than what is presently applied in many countries. For further info see 4.3.4.6.	width between countries and towards TSI CR INF.	Ref. [10] & RGS GC/RT5021 [11]
Infrastructure Operational/ organisational	P-24	Establish EU-wide intervention and/or immediate action limit for cant variations. In addition it should be considered to introduce a limit for excessive cant in track positions where trains are likely to stop or operate at low speed. Many derailments occur in track sections with narrow curves and high cant at low speed. For further info see 4.3.4.7.	Swiss & Norwegian track regulations	Swiss & Norwegian track regulation, [12, 13, 14]
	P-25	Establish EU-wide intervention and/or immediate action limit for height variations and cyclic tops which does not exist in Final draft TSI for Conventional rail infrastructure. For further info see 4.3.4.8.	GB and Norway at least.	RGS GC/RT5021 [11] and Norwegian track regulation [15]

Table 8: Infrastructure preventive measures against derailment (adapted from DNV final report for European Railway Agency on Freight Train Derailment – 2011)

The preventive measure number 15 (P-15) identified as an important preventive measure for safeguarding the trains against derailment was Bogie performance monitoring/Bogie lateral instability detection (bogie hunting). However, in the same study it was also found that this type of detection system despite its lucrativeness in identifying train bogies that exhibit poor performance was only applied in few countries, (Table 9).

Measure Number	Description	Category	Comment
P-10	Hot axle box (hot bearing) detectors	Medium	The technology exists, and is already implemented in some locations. However, the time to procure, install, train personnel and test such equipment is unlikely to be achievable in the short term.
P-11	Acoustic bearing monitoring equipment	Medium	The technology exists, although is not implemented (other than in test locations) in the target countries. It may require a lengthy implementation programme, although it is considered to be achievable within 5 – 10 years.
P-12	Hot wheel and hot brake detectors	Medium	These are often provided as a function of hot axle box detectors, and for the purposes of this assessment are jointly considered with P-10.
P-13	Wheel load and wheel impact load detectors	Medium	The technology exists, and is already implemented in some locations. However, the time to procure, install, train personnel and test such equipment is unlikely to be achievable in the short term.
P-14	Dragging object and derailment detectors		Derailment detectors considered at M-7. Regarding dragging object detectors these devices would have to be fitted at a very high frequency along the track, with high installation costs and maintenance costs. On the basis that the cost would be prohibitive and we have not considered these further.
P-15	Bogie performance monitoring/Bogie lateral instability detection (bogie hunting)	Medium	The technology exists, although is not implemented (other than a small number of locations) in the target countries. It may require a lengthy implementation programme, although it is considered to be achievable within 5 – 10 years.
P-16	Wheel profile measurement system / Wheel profile monitoring unit	Medium	The technology exists, and is already implemented in some locations. However, the time to procure, install, train personnel and test such equipment is unlikely to be achievable in the short term.
P-17	Not used		
P-18	Sufficient availability of maintenance resources	Short	This is a matter of recruitment and training. It is considered that this could be achieved within the short term.
P-19	Clearance of obstructions from flange groove (particularly at level crossings)	Short	This is a matter of potentially increasing inspections at certain locations. It is considered that this could be achieved within the short term.
P-20	Ultrasonic rail inspection	Short	This is a matter of potentially increasing inspections at certain locations. It is considered that this could be achieved within the short term.
P-21	Track geometry measurement of all tracks	Short	This is a matter of potentially increasing inspections at certain locations. It is considered that this could be achieved within the short term.
P-22	EU-wide intervention/action limits for track twist	Medium	Such measures would involve extensive consultation with IMs, and possibly a revision to existing TSIs. This is unlikely to be achievable within the short term.
P-23	EU-wide intervention/action limits for track gauge variations	Medium	Such measures would involve extensive consultation with IMs, and possibly a revision to existing TSIs. This is unlikely to be achievable within the short term.
P-24	EU-wide intervention/action limits for cant variations	Medium	Such measures would involve extensive consultation with IMs, and possibly a revision to existing TSIs. This is unlikely to be achievable within the short term.
P-25	EU-wide intervention/action limits for height variations and cyclic tops	Medium	Such measures would involve extensive consultation with IMs, and possibly a revision to existing TSIs. This is unlikely to be achievable within the short term.
P-26	Flange lubrication of locomotives	Medium	The adoption of such measures, where not currently applied, would require consideration of the application parameters, surveys of IMs' infrastructure and RUs' locomotives to identify lubrication locations and then engineering work to implement this measure. It is not considered this could be achieved in the short term.

Table 9: Time categorization of existing preventative measures against derailment (adapted from DNV final report for European Railway Agency on Freight Train Derailment -2011)

Market research for the technical preventive measures identified were also analyzed for the European Railway Agency by DNV. The table below reports the results of the market assessments.

Measure	Description	Quantity of Suppliers	Market Size	Market Conditions
P-10 and P-12	Hot axle box (hot bearing) detectors / Hot brake detectors	There are at least 10 suppliers in the market with each supplier producing at least one device.	We estimate the existing market size to be around 1,500 installed devices in the target countries, and around 8,000 world-wide. The potential market size / growth is likely to be in countries which do not currently use these devices.	This is a mature market with a good range of suppliers and devices. It is an existing European requirement that devices of this type are used in certain locations and hence possible further regulation is unlikely to provide one supplier with a competitive advantage. Pricing levels are likely to be stable.
P-11	Acoustic bearing monitoring equipment	There are at least 3 suppliers of device of this type.	There is no existing market in the target countries, although at least one country is testing this technology. It is known that at least 80 such installations operate in the USA and China. The potential market size is not considered to be very large due to high cost and (relatively) low installation density	The small number of existing suppliers may enjoy a dominant position if regulation were introduced regarding these measures. Prices are currently high, but more volume and new entrants may force prices down.
P-13	Wheel load and wheel impact load detectors	There are at least 10 suppliers in the market with each supplier producing at least one device.	We estimate the existing market size to be around 150 installed devices in the target countries. In the USA there are at least 130 installations. The potential market size is not considered to be very large due to high cost and (relatively) low installation density	This is a mature market with a good range of suppliers and devices. Regulation in this area is unlikely to provide one supplier with a competitive advantage. Pricing levels are likely to be stable.
P-15	Bogie performance monitoring/Bogie lateral instability detection (bogie hunting)	There are at least 5 suppliers in the market with each supplier producing at least one device.	We estimate the existing market size to be very small at present in the target countries – probably in single figures. In the USA there are at least 30 installations. The potential market size is not considered to be very large due to high cost and (relatively) low installation density	The small number of existing suppliers may enjoy a dominant position if regulation were introduced regarding these measures. Prices are currently high, but more volume and new entrants may force prices down.
P-16	Wheel profile measurement system / Wheel profile monitoring unit	There are at least 9 suppliers in the market with each supplier producing at least one device.	The size of the existing market is difficult to estimate due to the varying technologies and different functions offered by such systems, however we consider the market to be relatively small. Few IMs / RUs indicated they use such systems. We estimate the size of market in the target countries to be in double figures, but not significant. One supplier estimates the total market size to be fewer than 500.	This is a niche market, although we have noted that solutions and prices can vary significantly. However, this is not likely to be a high volume market.
M-1	Derailment detection devices	There are at least 4 suppliers in the market with each supplier producing at least one device.	We estimate that about 2,000 wagons are fitted with devices of this type. The potential market size is large, potentially every freight wagon operating in the target countries.	This is a market that is expanding in terms of the numbers of suppliers, although one supplier has a dominant position. Costs are relatively low and as the supplier base grows may reduce further, especially if larger volume sales are anticipated.

Table 10: Market assessment results for existing preventive measures against derailment (adapted from DNV final report for European Railway Agency on Freight Train Derailment – 2011)

The results on the market assessment for what concerns bogie performance/Bogie instability detection (bogie hunting) technical measures estimated a very small market size for such systems served by few suppliers – at least 5 suppliers in the market with each supplier producing at least one device [51].

Given that derailment is the most severe repercussion encountered in railway operations, any measure or technology which is cost-effective and with high potential in mitigating derailment or predicting its occurrence should be pursued and brought to the market to better help the railways maintain its position as the safest mode of transport. It is in this view that bogie (truck) hunting detection was thought of as an important technology that still needs to be widely implemented and if that is achieved, it may further help the infrastructure managers facilitate improvements and optimization of safety and maintenance decision-making for railway infrastructure.

To this regard, a world class innovative bogie (truck) hunting detection system realized by DMA srl (Turin) is presented in the next chapter. This system is a feasible technical solution to the problem confronted in the entire Part 1 of this thesis.

9. DMA Truck Hunting Measurement (THM) system

DMA (Turin) is a global leader in solutions for railway infrastructure monitoring and diagnostics. DMA's spectrum of products ranging from train borne systems to wayside monitoring systems and software solutions for data analytics allow IMs to have a highly detailed accurate condition data of their infrastructures. Dedicated to the detection of the bogie/truck hunting is the truck hunting measurement system (THM). THM is a wayside system that detects hunting through real-time measurements of wheel-rail interface parameters that influence this lateral motion of wheelsets on the track.

9.1. THM measurement technology

The THM is a non-contact wayside measurement system that deploys laser technology for the measurement and derivation of some crucial wheel-rail parameters useful for understanding the running behaviour of wheelsets on the track. The system therefore enables highly detailed condition assessment of truck/bogie hunting.

The THM measurement device is an easily installable module, installed between two consecutive sleepers on a tangent track in a manner that it does not affect normal traffic operation or structural gauge restrictions. The THM device is installed with reference to the center of the track, such that the center of the device corresponds to the center of the track and detection of wheels passing are referenced to this coordinate system. Each device has two lasers, one on each lateral end that measure the distance of passing wheels for each wheelset.

The system applies the 'laser triangulation' principle for its measurements. Laser triangulation involves the laser source projecting a beam of light on the cross section of interest in this case the passing wheel and high-speed cameras capturing the image of that section for further analysis. This further analysis is done through application of mathematical algorithms to process the image and deliver the accurate measured parameters within their specified accuracies. The THM system is a passive system that deploys an inductive sensor placed at a predetermined distance from the THM devices to detect the proximity of incoming vehicles so as to activate the system ready for measurement.

Klingel's formula as introduced and described in Part I of this study gives us the kinematic oscillation for single wheelset. However, bogies (trucks) consist of two wheelsets, therefore a correction factor is required in the Klingel formula to cater for the additional wheelset. The THM in its measurements considers this variation, and the following modified Klingel's formula that considers the wheelbase (a) is applied to obtain the hunting wavelength.

$$\lambda = 2\pi \cdot \sqrt{\frac{r_0 e}{2\tan\gamma}} \cdot \sqrt{1 + \frac{a}{e}}$$

Equation 5. Modified Klingel equation considering wheelbase for 2 axle-wheelset bogie

Figure 51 shows a typical example of a THM module installed on the track.

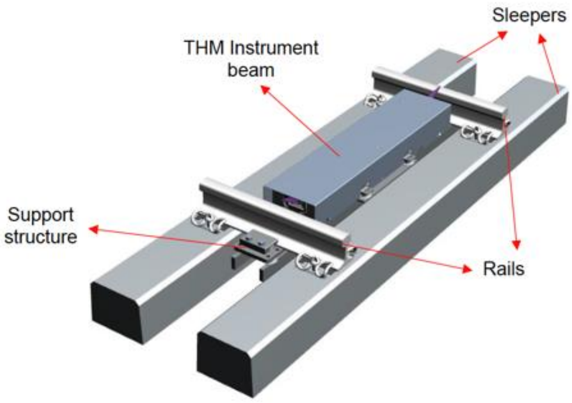


Figure 51: DMA Truck hunting measurement (THM) device installed on the track.

The figures below illustrate the DMA truck hunting measurement (THM) modules on the track in passive state (image on the left) and measurement state as wheelsets pass over the modules (image on the right).

Figure 52: THM devices installed on the track – passive state (left) and measuring state (right)

As the wheelsets enter and exit a THM module, the absolute value of the wheel distance with reference to center of the track to which the THM is set gives the lateral position asymmetry.

The figure below illustrates four positions (A, B, C and D) of the bogie as wheelsets enter and exit a THM module.

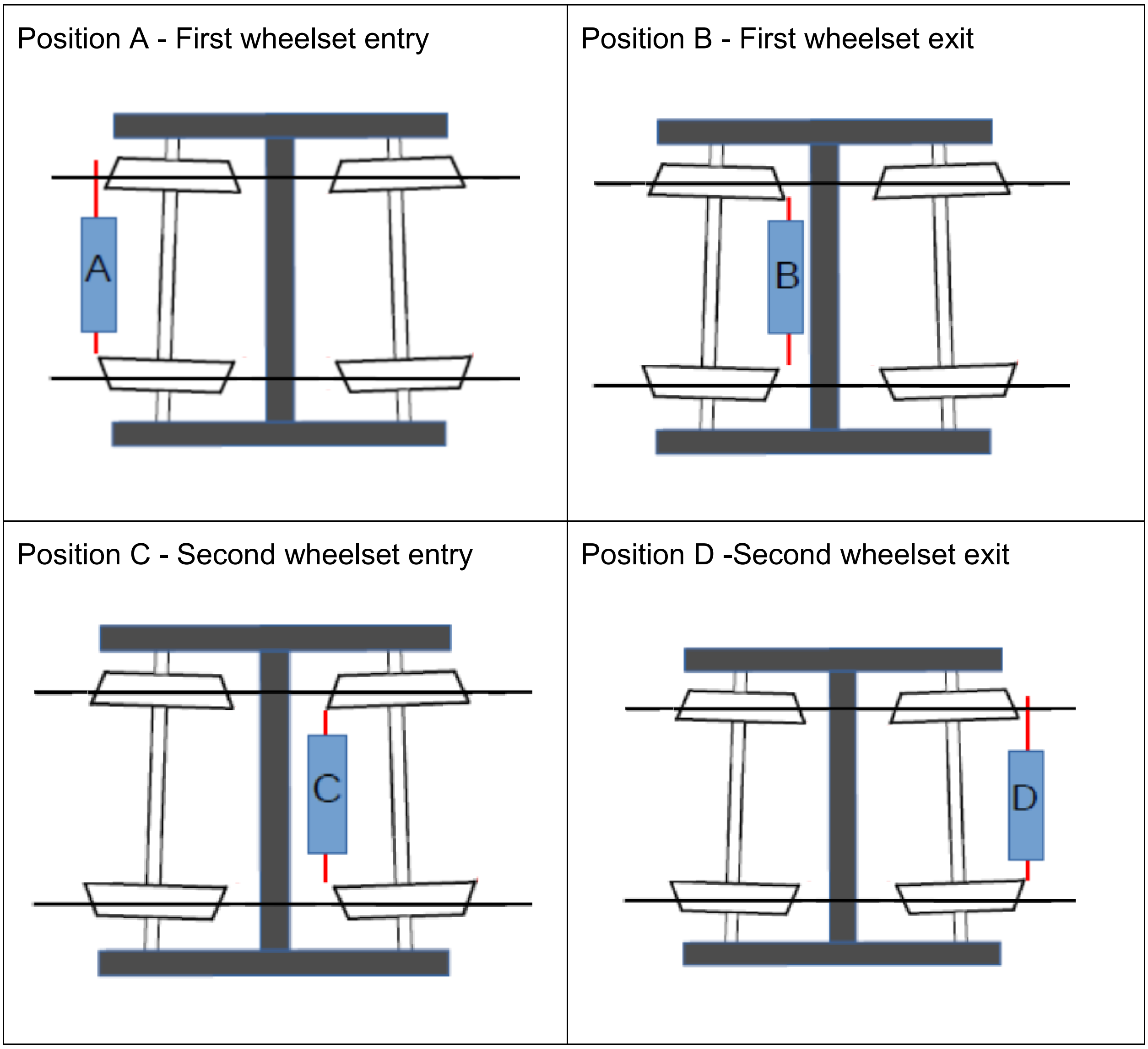


Figure 53: Single THM module measuring lateral displacement of a 2-axle wheelset bogie in four various positions (A, B, C and D)

9.2. THM measured parameters.

Measuring the kinematic oscillation of the wheelsets through the measurement technology described in the precedent subchapter and by applying the modified Klingel formula as previously shown (Equation 5), information useful to evaluate the lateral performance of a vehicle on the track. Table 11 shows delivered parameters by the THM system.

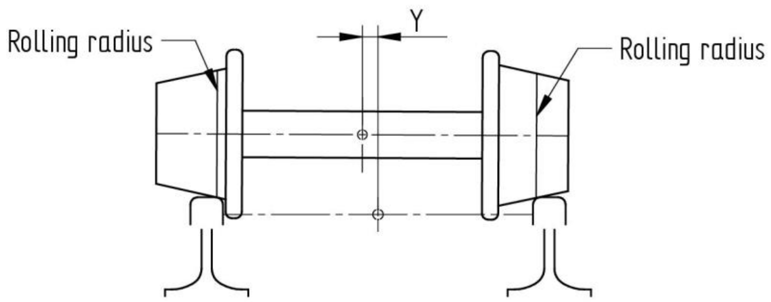
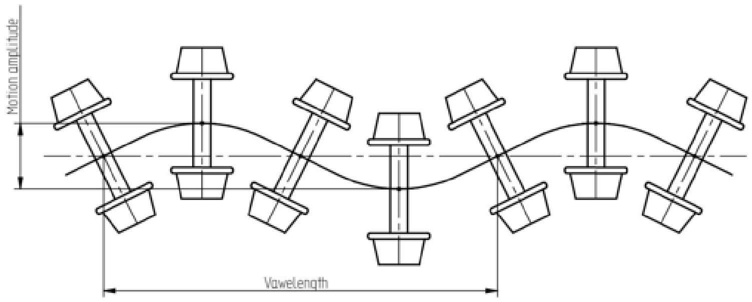
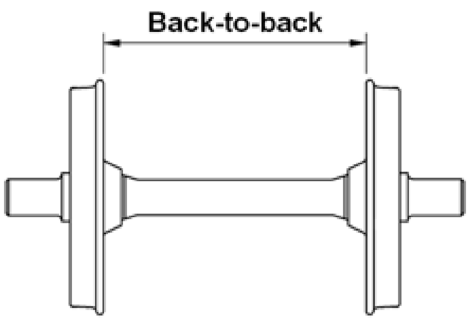
Parameter	Definition	Symbol [Unit]
Wheelset average lateral displacement		Y [mm]
Wheelset hunting motion amplitude		Wa [mm]
Wheelset hunting motion wavelength		Λ [mm]
The Back-to-Back gauge in several positions along the wheel		BtoB [m]

Table 11: THM system output

In addition to the direct measured parameters listed in the table above, the THM also provides:

- Estimation of equivalent conicity
- Estimation of rolling radius.

From the THM output, poor performance of wheelsets on the track can be identified and predictions on wear or vehicle stability can be availed way before further deterioration is manifested. Therefore, THM provides a proactive solution for the maintenance management of the wheel-rail interface.

The measurement accuracy of the above listed output depends on the THM configuration adopted as demonstrated in the next section.

9.3. THM design and configuration

To have an all-round view of the lateral sinusoidal motion of wheelsets on the track, more than one THM module is required, actually various THM modules are needed (typically 7 -10 modules).

Figure 54 and 55 illustrate why a single module is not enough to give adequate information about the vehicle hunting. If only one module is present, we may fall in the zero angle of attack condition i.e, central position that displays ideal state and symmetry (A), however, this may not be the whole story. For another wheelset or different position in the sinusoidal path we may have a situation where the wheelset is not centered, for instance a severe case with flange in contact with the rail (B).

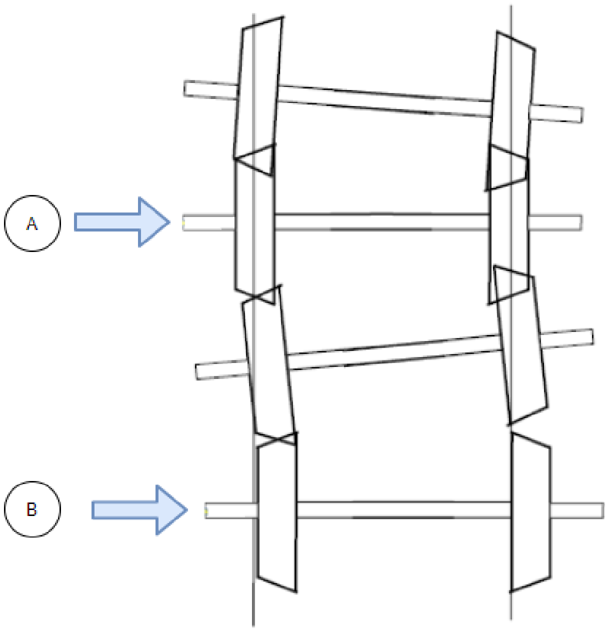


Figure 54: Two points of measurements (ideal and non-ideal) that justify the need of more than one THM module – case 1

Another effect that justifies the need for more than one THM module is the wheel parallelism and orthogonality to the axle. If measurement is done by a single module at position (C) the back-to-back gauge may be ideal, but again may not tell the entire story as another measurement at position (D) may show behaviour far from the ideal case.

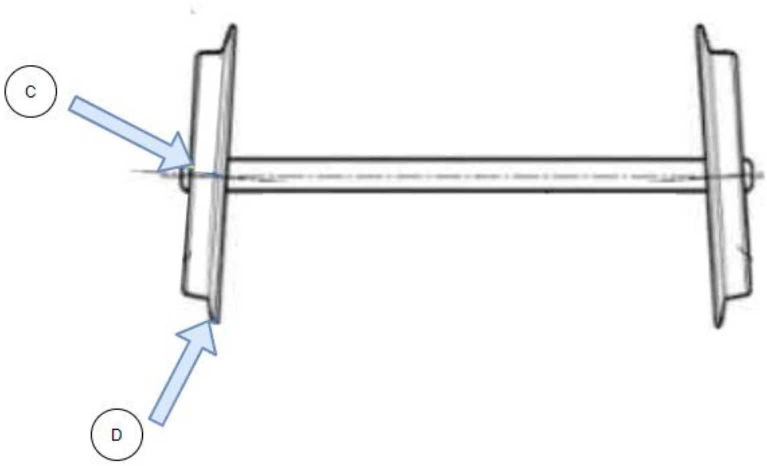


Figure 55: Two points of measurements (ideal and non-ideal) that justify the need of more than one THM module – case 2

This raises a design challenge, as to what configuration the numerous THM modules should adopt. There is no unique solution to this design challenge. Various configurations may be adopted based on infrastructure manager or final client specifications depending on what details need to be portrayed in the measurements, which consequently this influences the measurement accuracy to be guaranteed.

THM modules can be configured in various ways based on:

- Choice of number of THM modules to be installed.
- Choice of spacing between THM modules.
- Choice of constant/non constant spacing between THM modules.
- Choice of the range of hunting lengths.

9.3.1. Development and optimization

In the feasibility studies for developing or optimizing a THM configuration i.e. (number of modules, spacing between modules, constant or non-constant spacing etc.), simulations are performed by a dedicate software for thousands of wheelsets of various characteristics and under various conditions and constraints. The aim is to understand the expected performances and accuracies against required THM outputs for a certain configuration through statistical analysis.

For optimization or new configurations simulation helps to benchmark the expected output and their accuracies to field results as obtained by existing system in service

9.3.1.1. Simulation method

Simulation is done for different types of configurations (Figure 56 and 57) using thousands of sinusoidal wheelset trajectories (samples) for statistical validation, under following conditions:

1. Amplitudes are random.
2. Sinusoidal trajectories phase is random.
3. THM uncertainty is assumed to be ± 0.2 mm.
4. The trajectory fitting is made by a minimum error algorithm.
5. The error is calculated as the mean value of thousands of samples.
6. The variation is estimated by the 2σ (95%)

The simulation tests the error estimation for the following parameters:

- Wheelset displacement
- Wheelset motion amplitude
- Wheelset hunting wavelength

Figure 52 & 53 illustrate various examples of THM configurations analyzed through simulation.

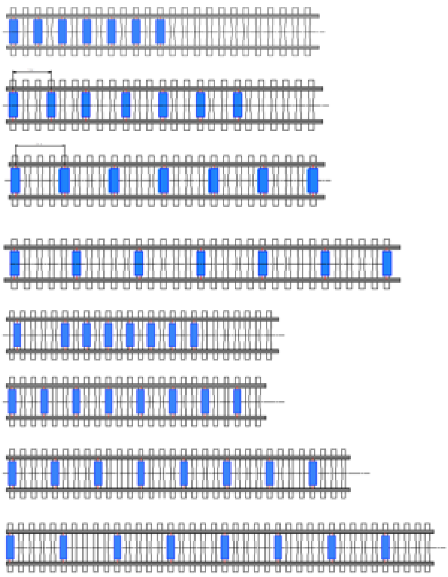


Figure 56: THM configurations – less than 10 modules (adapted from DMA product specification)

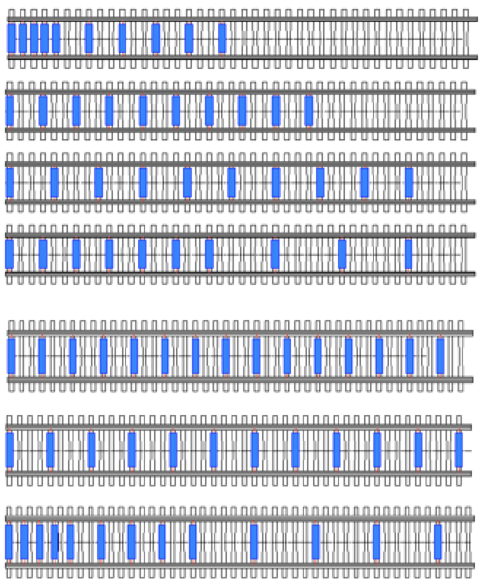


Figure 57: THM configurations – 10 modules and above (adapted from DMA product specification)

9.4. Measurement accuracy

From the results obtained through simulation, DMA has developed a further study on the relations between accuracies, range of wavelengths and the various THM configurations.

The table below shows accuracies for a range of wavelengths between 4 and 20 m of 5 types of configurations.

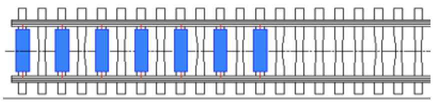
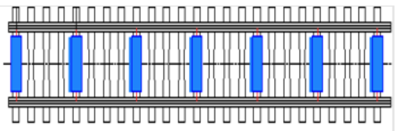
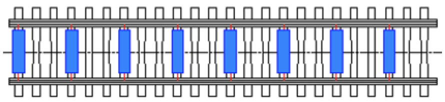
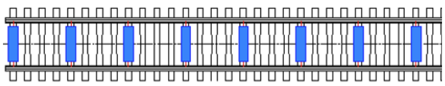
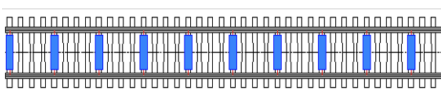
THM Configuration	Wm [mm]	Wa [mm]	AOA (α) [mrad]	λ(short) [m]	λ (long) [m]
7THMx1,34/8m 	±2.0 mm	±4.0 mm	±0.5 mrad	2 m	> 10 m
7THMx2,4/14,4m 	±0.5 mm	±1.0 mm	±0.5 mrad	0.5 m	±6 m
8THMx2,4/16,8m 	±0.4 mm	±0.5 mm	±0.5 mrad	0.5 m	±3 m
8THMx3/21m 	±0.2 mm	±4.0 mm	±0.5 mrad	3 m	±2 m
10THMx2,4/21,6m 	<±0.2 mm	±0.3 mm	±0.5 mrad	0.2 m	±1.5 m

Table 12: THM measurement accuracies for various configurations

Where:
- λ(short) – refers to short hunting wavelengths (4-10m)
- λ(long) – refers to short hunting wavelengths (10-20m)

9.5. Field measurements

In this section a brief analysis on bogie stability and wheelset running performance based on real measurements conducted by a THM system installed on a tangent track in Germany is presented. The figure below illustrates the THM system (7 modules configuration) in question.

Figure 58: DMA truck hunting measurement (THM) system-7 module configuration installed on a tangent track, Germany

Thousands of measurements of various vehicles with different characteristics have been performed on the THM system illustrated above (Figure 58). Statistics analysis based on 14000 measured wheelsets has been performed and results of interest to this study reported in the figures below.

9.5.1. Case 1: Asymmetric wheelsets

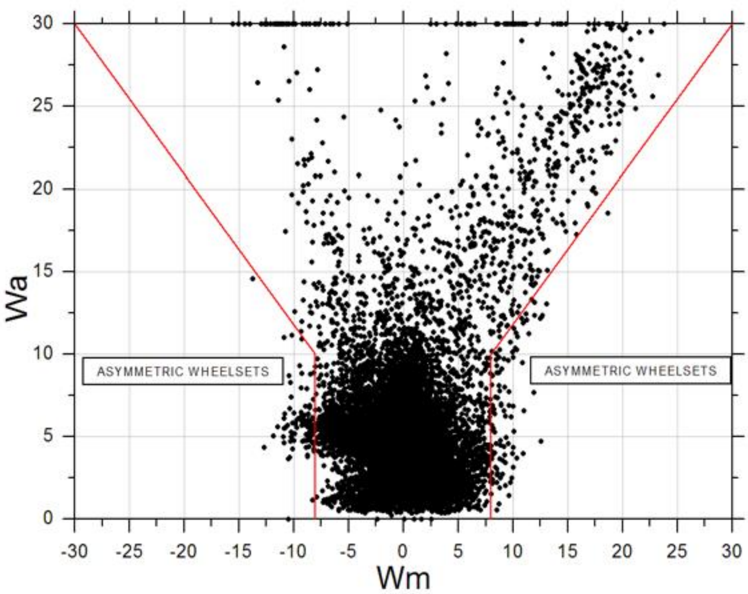


Figure 59: THM real measurement analysis – asymmetric wheelset statistics

The Wa-Wm diagram (Figure 59) it is shown the wheelset asymmetry in terms of left-right radius difference; it is a function of the sinus hunting amplitude (Wa) and average position in the track (Wm).

In ideal conditions, the wheelset should run centred, and the amplitude should be small (less than the nominal track rail-flange clearance). A big amplitude (for instance Wa >13 mm) normally indicates a situation of worn flange, this might still guarantee safe operation, but measured wheel parameters may better shed light to predictions by the THM.

In this regard, DMA has enriched its product spectrum by providing integrated solutions such as the THM + WPMS, which is not only a commercially sound strategy, but technically powerful approach and solutions towards predictive maintenance.

The figure below illustrates the THM 7 module configuration integrated to a WPMS.

Figure 60: DMA truck hunting measurement (THM) system integrated to a wheel profile measurement system (WPMS) installed on a tangent track, Germany

To highlight the power of a THM system integrated to a WPMS system, an example of a poor performing wheelset as detected by the THM and further validated by wheel profile measurements is illustrated below.

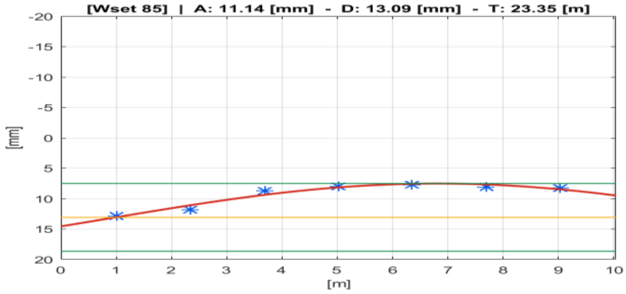
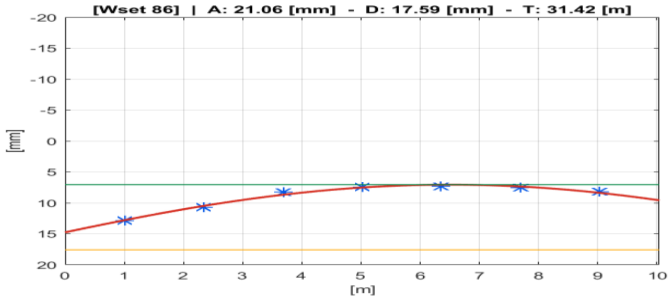
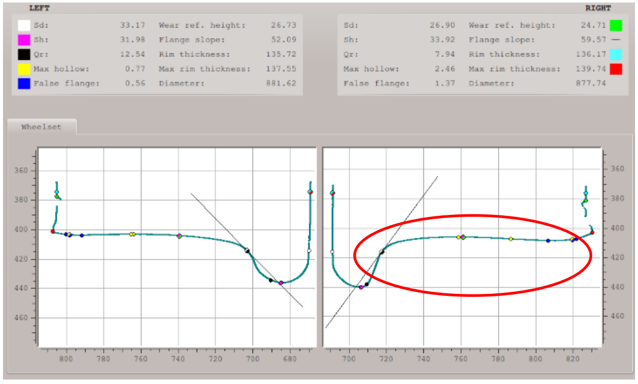
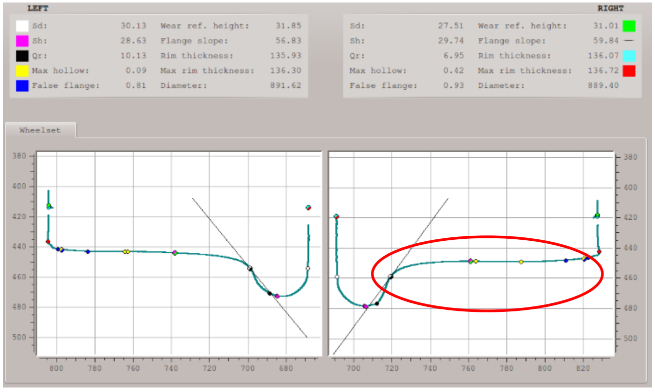
<table>
<tr>
<td>Wheelset 85 - THM

</td>
<td>Wheelset 86 -THM

</td>
</tr>
<tr>
<td colspan="2">The THM detects a very large displacement of the wheelset motion which could be dangerous.</td>
</tr>
<tr>
<td>Wheelset 85 – WPMS
</td>
<td>Wheelset 86 -WPMS
</td>
</tr>
<tr>
<td colspan="2">From the WPMS measurements the detection of a large wheelset displacement is validated. Furthermore, WPMS puts to light the reason for the detected anomality by the THM. In this case the reason is an abnormal flange wear on the right wheel.</td>
</tr>
</table>

Figure 61: THM predictions backed up with WPMS data from an integrated system

9.5.2. Case 2: Unstable wheelsets

The Wλ-Wa diagram (Figure 62) identifies potential unstable wheelsets. A criterion for this categorization is that a short wavelength and a big amplitude is a sign of a potential unstable wheelset as highlighted by the red line in the figure below.

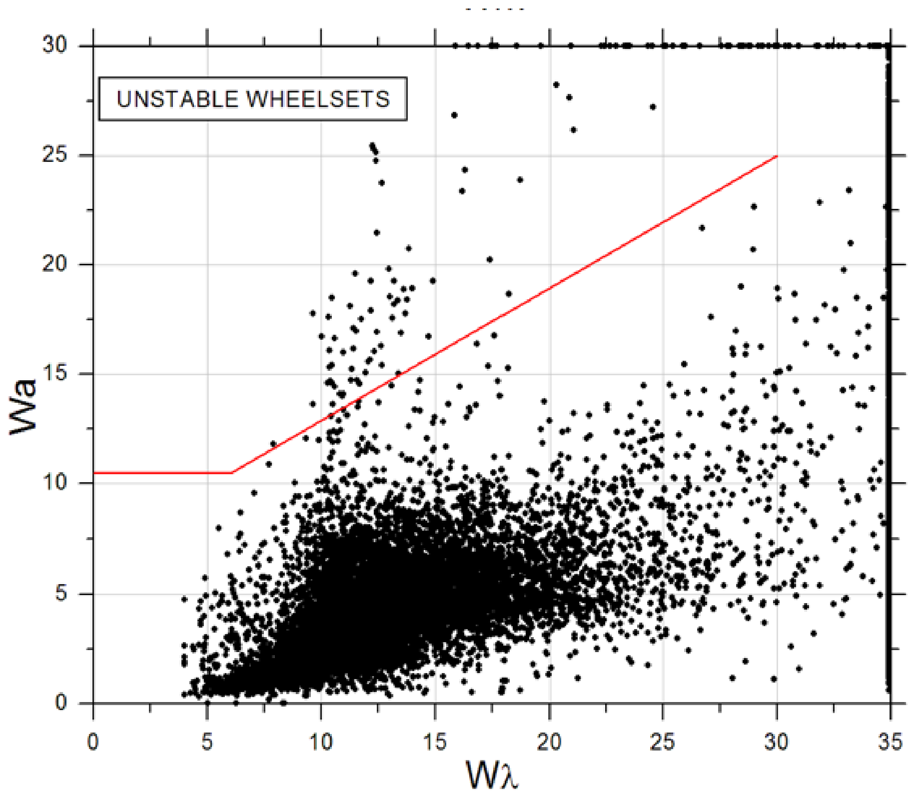


Figure 62: THM real measurement analysis – asymmetric wheelset statistics

10. DMA CONTACT software – wheel -rail contact analysis

As seen in PART I, equivalent conicity and rolling radius difference are fundamental parameters to the wheel-rail contact problem especially in describing the wheelsets running behaviour on the track and the vehicle dynamic instability – hunting. Therefore, it is important to manage wheel and rail profiles in the first place and in the second place be able to accurately measure these parameters that characterize vehicle dynamic performance.

This chapter gives an insight in to a versatile software tool dedicated to wheel-rail contact analysis. The DMA CONTACT software package is dedicated to simulation of wheel-rail contacts as well as wheel-rail interaction analysis based on real field measurements. The software delivers output including rolling radius difference function graph, equivalent comity, wheelset wavelengths etc. in accordance to standards EN 15302 and EN 14363. An example of CONTACT output is benchmarked to a case application example of reference profiles set in the EN 15302 to evidence the conformance of the former to the latter.

CONTACT provides the following analysis:

Wheel – Rail contact		Analysis
Standard wheel	Standard rail	Simulation analysis
Standard wheel	Measured rail	Rail/Wheel maintenance - based analysis
Measured wheel	Standard rail	
Measured wheel	Measured rail	

10.1. Simulation

For simulation analysis, the lateral displacement of the wheelset on the track is simulated, from the far-left position (green, in the figure) to the far-right position (red).

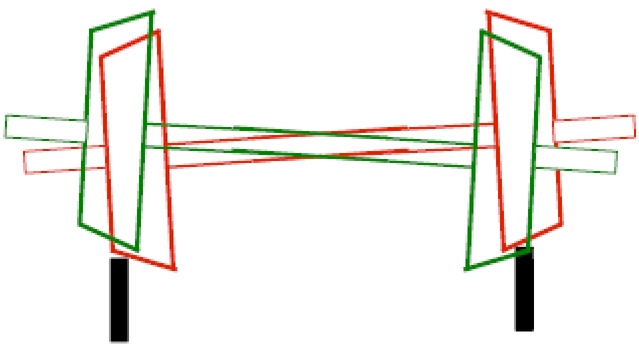


Figure 63: Wheelset lateral displace simulation for contact points analysis.

The simulator starts placing the wheelset perfectly centered on the track (0) position: the midpoint in between the wheels is on the center of the track); the relevant contact points are found. The process is then repeated displacing the wheelset to the right (positive displacement) and to the left (negative displacement). The process stops when the contact point climbs on the flange (in both directions).

Since the contact point is computed between two perfectly rigid bodies (as per the EN 15302); the double contact condition does not exist.

10.1.1. Case 1: Wheel A/Rail A (reference profiles established in the EN 15302)

Annex D of the standard EN 15302 provides a series of reference profiles, both wheel and rail. Section D.1 of the Annex provides a wheel reference profile (Wheel A) for the right wheel together with analytic definition of how z-coordinates of the profile are derived. For simplicity purposes, a table reporting all coordinates of the profile (y and z) is also provided. Similarly, Section D.5 of the Annex provides a rail reference profile (Rail A) for the right wheel together with analytic definition of how z-coordinates of the profile are derived. Also, here a table reporting all coordinates of the profile (y and z) is provided for simplicity purposes.

D.1 Wheel A

D.1.1 Drawing

Dimensions in millimetres

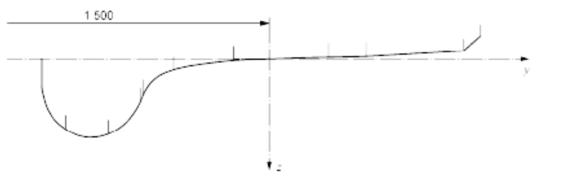


Figure D.1 — Wheel A

D.1.2 Analytic definition

z coordinates of the profile are defined in the following ranges:

From y = -70	to y = -62,764 7	: $z = +9{,}519\,3 + (20{,}5^2 - (y + 49{,}5)^2)^{0{,}5}$
From y = -62,764 7	to y = -49,662 5	: $z = +16 + (12^2 - (y + 55)^2)^{0{,}5}$
From y = -49,662 5	to y = -39,764 5	: $z = +8{,}834\,9 + (20^2 - (y + 58{,}558\,3)^2)^{0{,}5}$
From y = -39,764 5	to y = -38,737 2	: $z = -93{,}576\,7 - 2{,}747\,5 \times y$
From y = -38,737 2	to y = -29,459 1	: $z = +17{,}642\,1 - (14^2 - (y + 25{,}581\,6)^2)^{0{,}5}$
From y = -29,459 1	to y = -10,874 9	: $z = +97{,}16492 - (96{,}760\,5^2 - (y + 2{,}659\,4)^2)^{0{,}5}$
From y = -10,874 9	to y = +18,417 3	: $z = +344{,}508\,1 - (345^2 - (y - 18{,}417\,3)^2)^{0{,}5}$
From y = +18,417 3	to y = +30	: $z = -0{,}4919 + 0 \times y$
From y = +30	to y = +60	: $z = +1{,}509\,1 - 0{,}066\,7 \times y$
From y = +60	to y = +65	: $z = +57{,}507\,1 - 1 \times y$

D.5 Rail A

D.5.1 Drawing

Dimensions in millimetres

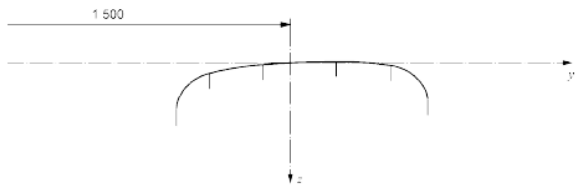


Figure D.5 — Rail A

D.5.2 Analytic definition

z coordinates of the profile are defined in the following ranges:

From y = -32,639 5	to y = -23,240 1	: $z = 15{,}899\,0 - (13^2 - (y + 19{,}639\,5)^2)^{0{,}5}$
From y = -23,240 1	to y = -7,874 9	: $z = 80{,}277\,9 - (80^2 - (y + 1{,}082\,5)^2)^{0{,}5}$
From y = -7,874 9	to y = +13,098 9	: $z = 299{,}483\,5 - (300^2 - (y - 17{,}596\,6)^2)^{0{,}5}$
From y = +13,098 9	to y = +28,670 9	: $z = 79{,}508\,2 - (80^2 - (y - 14{,}298\,2)^2)^{0{,}5}$
From y = +28,670 9	to y = +39,270 5	: $z = 13{,}598\,4 - (13^2 - (y - 26{,}335\,3)^2)^{0{,}5}$

Figure 64: Reference profiles Wheel A/Rail A coordinates (adapted from EN 15302, Annex D)

In Annex E of the standard, calculation results of combination of reference profiles is provided. The EN 15302 calls for the subsequent output:

- rolling radius difference (Δr), necessary to calculate the equivalent conicity
- tan γa
- tan γe: equivalent conicity
- representation of the contact points
- representation of the curves of the kinematic rolling movement of the wheelset on track (however, this is stated as not normally necessary)

The figure below shows the plotted results in graphical representation for Wheel A / Rail A combination.

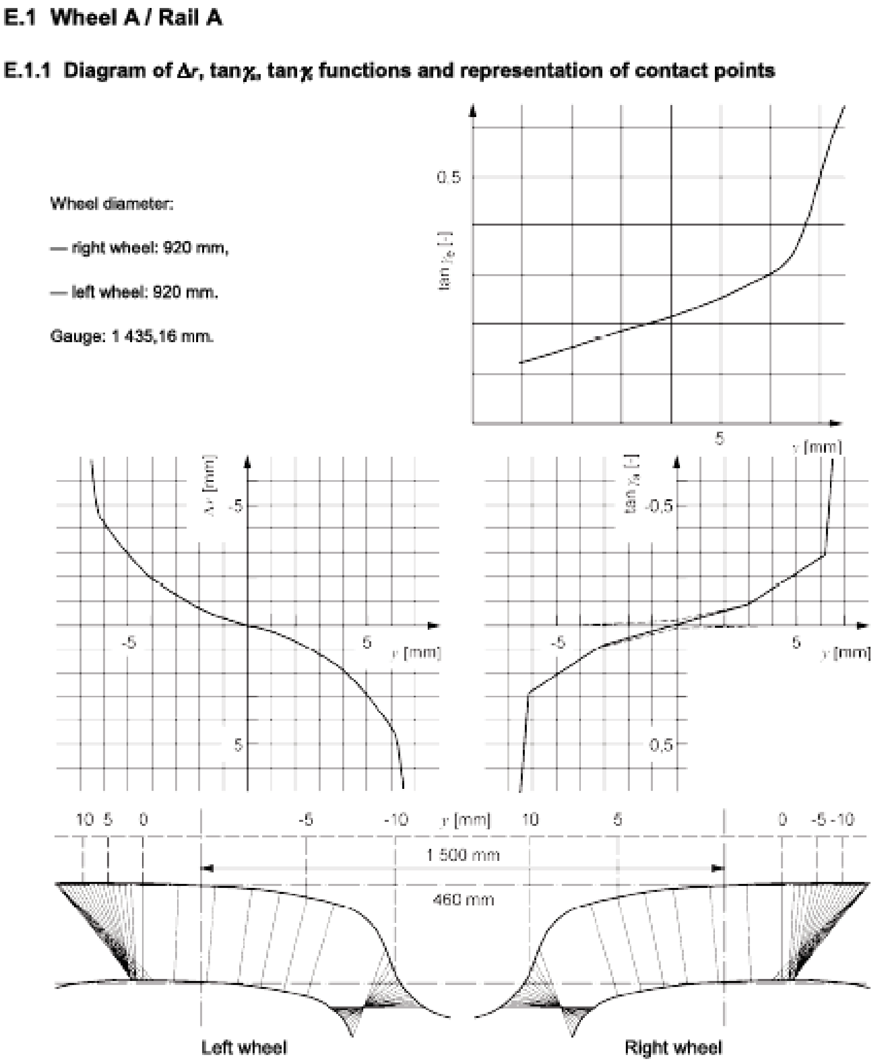


Figure 65: Reference profiles Wheel A/Rail A calculation results of combination (adapted from EN 15302, Annex E)

The similar analysis was done utilizing the CONTACT software, and the results were conforming to the ones in the standard.

CONTACT wheel-rail contact results for reference profiles Wheel A / Rail A are reported in Appendix 1.

Similar approach was adopted to analyze the following combinations for real wheel and rail profiles.

10.1.2. Case 2: ORE S1002 worn wheel profile / UIC 60 rail profile (at 1435 mm gauge and 1:20 cant)

Results reported in Appendix 2.

10.1.3. Case 3: ORE S1002 worn wheel profile / UIC 60 rail profile (at 1435 mm gauge and 1:40 cant)

Results reported in Appendix 3.

11. Conclusions

In this research project, it has been shown why the wheel-rail interface is critical to the safe and efficient operation of a railway network. The trend towards improved performance and enhanced operation capacity in terms of higher speed and higher axle load directly implies increase in stresses at the wheel-rail contact patch, which if not monitored could lead to deterioration phenomena that have a huge impact on infrastructure managers in terms of maintenance costs. Therefore, there is need for proactive strategies that can provide accurate condition data of the rails given the interaction with vehicle wheels and vice-versa. The first step in confronting the wheel-rail interaction is that of determining the wheel profile and the rail profile and their compatibility that guarantees the smooth running on the track. The equivalent conicity which is the parameter that governs the wheel-rail geometric interaction is addressed in this study and methods of calculating it provided together with real examples from field measurements. It is also of paramount importance to understand the running behaviour of vehicles on the track and in case of defective behaviour, IMs need to know the effect of such behaviours on the track integrity. The thesis proposes a simple but yet powerful system for detection of anomalous running behaviour of bogies (trucks) which provides IMs with valuable information in advance regarding response of their track to poor running behaviour of vehicles. This information integrated to other data regarding the condition of the infrastructure can help IMs predict wear and other deterioration phenomena and thus cutting down on the high track maintenance costs.

Bibliography

[1] EN 15302:2008+A1:2010 - Railway applications - Method for determining the equivalent conicity

[2] EN 14363:2016+A1:2018 – Railway applications. Testing and Simulation for the acceptance of running characteristics of railway vehicles. Running Behaviour and stationary tests.

[3] EN 13848-1 - Railway applications – Track – Track geometry quality – Part 1: Characterization of track geometry

[4] Magel, Eric, and Kalousek, Joe. "Designing and Assessing Wheel/rail Profiles for Improved Rolling Contact Fatigue and Wear Performance." Proceedings of the Institution of Mechanical Engineers. Part F, Journal of Rail and Rapid Transit 231.7 (2017): 805-18. Web.

[5] Lewis, R., and Olofsson, U. Wheel—rail Interface Handbook. Woodhead, 2009. Web.

[6] Skrickij, Viktor, Šabanovič, Eldar, Shi, Dachuan, Ricci, Stefano, Rizzetto, Luca, and Bureika, Gintautas. "Visual Measurement System for Wheel-Rail Lateral Position Evaluation." Sensors (Basel, Switzerland) 21.4 (2021): 1297. Web.

[7] Enblom, Roger. "Deterioration Mechanisms in the Wheel-rail Interface with Focus on Wear Prediction: A Literature Review." Vehicle System Dynamics 47.6 (2009): 661-700. Web.

[8] Fröhling, R. D. "Wheel/rail Interface Management in Heavy Haul Railway Operations-applying Science and Technology." Vehicle System Dynamics 45.7-8 (2007): 649-77. Web.

[9] Charles, G, Goodall, R, and Dixon, R. "Model-based Condition Monitoring at the Wheel-rail Interface." Vehicle System Dynamics 46.Sup1 (2008): 415-30. Web

[10] Magel, E, Roney, M, Kalousek, J, and Sroba, P. "The Blending of Theory and Practice in Modern Rail Grinding." Fatigue & Fracture of Engineering Materials & Structures 26.10 (2003): 921-29. Web.

[11] Wilson, Nicholas, Wu, Huimin, Tournay, Harry, and Urban, Curtis. "Effects of Wheel/rail Contact Patterns and Vehicle Parameters on Lateral Stability." Vehicle System Dynamics 48.Sup1 (2010): 487-503. Web.

[12] Sedghi, Mahdieh, Kauppila, Osmo, Bergquist, Bjarne, Vanhatalo, Erik, and Kulahci, Murat. "A Taxonomy of Railway Track Maintenance Planning and Scheduling: A Review and Research Trends." Reliability Engineering & System Safety 215 (2021): 107827. Web.

[13] Magel, Eric, Mutton, Peter, Ekberg, Anders, and Kapoor, Ajay. "Rolling Contact Fatigue, Wear and Broken Rail Derailments." Wear 366-367.SI (2016): 249-57. Web.

[14] Guler, Hakan. "Decision Support System for Railway Track Maintenance and Renewal Management." Journal of Computing in Civil Engineering 27.3 (2013): 292-306. Web.

[15] Wickens, A. H. "The Dynamics of Railway Vehicles—from Stephenson to Carter." Proceedings of the Institution of Mechanical Engineers. Part F, Journal of Rail and Rapid Transit 212.3 (1998): 209-17. Web.

[16] Su, Zhou, Jamshidi, Ali, Núñez, Alfredo, Baldi, Simone, and De Schutter, Bart. "Multi-level Condition-based Maintenance Planning for Railway Infrastructures – A Scenario-based Chance-constrained Approach." Transportation Research. Part C, Emerging Technologies 84 (2017): 92-123. Web.

[17] Kumar, S, Espling, U, and Kumar, U. "Holistic Procedure for Rail Maintenance in Sweden. "Proceedings of the Institution of Mechanical Engineers. Part F, Journal of Rail and Rapid Transit222.4 (2008): 331-44. Web
[18] Chandra, Chandra, Agarwal, and Agarwal, M. M. Railway Engineering. Oxford: Oxford UP, 2007. Print.
[19] Wang, Chen, Luo, Shihui, Xu, Ziqiang, Gao, Chang, and Ma, Weihua. "Research on Bogie Frame Lateral Instability of High-Speed Railway Vehicle." Shock and Vibration 2018 (2018): 1-13. Web.
[20] Pålsson, Björn A, and Nielsen, Jens C.O. "Wheel-rail Interaction and Damage in Switches and Crossings." Vehicle System Dynamics 50.1 (2012): 43-58. Web.
[21] Uyulan, Caglar, Gokasan, Metin, and Bogosyan, Seta. "Dynamic Investigation of the Hunting Motion of a Railway Bogie in a Curved Track via Bifurcation Analysis." Mathematical Problems in Engineering 2017 (2017): 1-15. Web.
[22] A. H. Wickens, "The dynamic stability of railway vehicle wheelsets and bogies having profiled wheels," International Journal of Solids and Structures, vol. 1, no. 3, pp. 319–341, 1965
[23] Shen, G, and Zhong, X. "A Design Method for Wheel Profiles According to the Rolling Radius Difference Function." Proceedings of the Institution of Mechanical Engineers. Part F, Journal of Rail and Rapid Transit 225.5 (2011): 457-62. Web
[24] N. K. Cooperrider and J. J. Gordon, "Shock and impact levels on North American locomotives," Journal of Sound and Vibration, vol. 318, no. 4-5, pp. 809–819, 2008.
[25] O. Polach, "Wheel profile design for target conicity and wide tread wear spreading," Wear, vol. 271, no. 1-2, pp. 195–202, 2011.
[26] H. True, "The dynamics of a railway freight wagon wheelset with dry friction damping the suspension," Vehicle System Dynamics, vol. 38, no. 2, pp. 159–168, 2004.
[27] Dendy Marshall, C. F., A History of British Railways down to the Year 1830, Oxford University Press, London, pp.147 – 148, 1938
[28] Esveld, Coenraad. Modern Railway Track. 2nd ed. Zaltbommel, The Netherlands: MRT, 2001. Print.
[29] Vickers, R.A. Cost Effective Maintenance of Railway Track. Thomas Telford, 1992. Web.
[30] Harry, T., Wu, H., and Guins, T., The Influence of Hollow-Worn Wheels on the Incidence and Costs of Derailments, Association of American Railroads/Transportation Technology Center, Inc. report R-965, February 2004
[31] Mace, M., Dibrito, D., Blank, R., Keegan, S., and Michael, Allran, Effect of Wheel Profiles on Gauge Widening Behaviour, Proceeding of ASME/IEEE Joint Railroad Conference, March, 1994
[32] Tournay, H. M. (1999). —Rail/wheel interaction from a track and vehicle design perspective,‖ IHHA 1999 STS—Conference Wheel/Rail Interface, Moscow

[33] Nadal, M.J., Locomotives a Vapeur, Collection Encyclopedie Scientifique, Biblioteque de Mecanique
Appliquee et Genie, Vol. 186, Paris, 1908.
[34] Blader, F.B., A Review of Literature and Methodologies in the Study of Derailments Caused by
Excessive Forces at the Wheel/Rail Interface, Association of American Railroads Report R-717,
December 1990

[35] Tunna, J., dos Santos, G. F. M., and Kina, E. J. (2009). ―Theoretical and service evaluation of wheel performance on frame brace trucks,‖ Proceedings from the Ninth International Heavy Haul Railways Conference, Shanghai

[36] Wickens, A H. "Steering and Stability of the Bogie: Vehicle Dynamics and Suspension Design." Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit 205.2 (1991): 109-22. Web.
[37] Iwnicki, Simon. Handbook of Railway Vehicle Dynamics. Baton Rouge: CRC, 2006

[38] Grassie, S. L. (2005). Rolling contact fatigue on the British railway system. Wear, 258, 1310-1318

[39] Cannon D.F., Edel, K.O., Grassie, S. L., and Sawley, K. (2003). Rail defects: an overview. Fatigue and Fracture of Engineering Materials and Structures, 26, 865-886

[40] Doherty, A. (2004). Making the business case to cut rolling contact fatigue. Railway Gazette International, 160, 403-406.

[41] Papaelias, M., Roberts, C., and Davis, C. L. (2008). A review of non-destructive evaluation of rails: state-of-the-art and future development. Journal of Rail and Rapid Transit, 22(4), 367-384
[42] Hiensch, M., and Smulders, J. (1999 June). Meeting the challenge of head checks. International Railway Journal
[43] (2001 July). Railtrack‘s costs go through the roof. Railway Gazette International, 157, 448

[44] Deutschl, E., et al. (2004). ―Defect detection on rail surfaces by a vision based system,‖ Proceedings from the IEEE Intelligent Vehicles Symposium, Parma, Italy
[45] Reynolds, O., On the efficiency of belts or straps as communicators of work, The Engineer, 27
November 1874

[46] Magel, E., and Sawley, K. (2006). Rail Surface Condition Alert – stage 1: Evaluation and calibration of surface crack measuring devices. CSTT report number CSTT-RYV-CAT-090

[47] https://shift2rail.org/wp-content/uploads/2021/06/Shift2Rail-Master-Plan_approved-by-S2R-GB.pdf

[48] https://www.unife.org/wp-content/uploads/2021/03/UNIFE-Vision-Paper-on-Digitalisation.pdf

[49] https://errac.org/wp-content/uploads/2019/03/122017_ERRAC-RAIL-2050.pdf

[50] European Commission White Paper (2011) - Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011DC0144&from=EN

[51] Det Norske Veritas – Assessment of freight train derailment risk reduction measures. Part A Final Report. Report for European Railway Agency – Report No: BA000777/01. Rev 01. 21 July 2011.

[52] Ambika Prasad Patra – Doctoral Thesis -Maintenance Decision Support Models for Railway Infrastructure using RAMS & LCC Analyses. Lulea University of Technology.

http://ltu.diva-portal.org/smash/get/diva2:999382/FULLTEXT01.pdf

[53] EN 13306:2010 – Maintenance – Maintenance terminology

[54] EN 50126-1: Railway Applications – The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS) – Part 1: Generic RAMS Process

[55] IEC 60050 – 192:2015 – International Electrotechnical Vocabulary (IEV) – Part 192: Dependability

[56] Saurabh Kumar (2006) - Study of Rail Breaks: Associated Risks and Maintenance Strategies, Technical Report. Lulea Railway Research Center (JVTC)

[57] Matin Sichani (2016), On Efficient Modelling of Wheel-Rail Contact in Vehicle Dynamics Simulation. KTH Engineering Sciences. Doctoral Thesis.

[58] Chiengson, C, Kaewunruen, S & Aikawa, A 2018, Nonlinear phenomena of short and long wavelength rail defects on vehicle-track interaction. in *13th World Congress on Computational Mechanics (WCCM XIII).* United States Association for Computational Mechanics, pp. 1388-1399, 13th World Congress on Computational Mechanics, New York, United States, 23/07/18

[59] https://en.wikipedia.org/wiki/System#cite_note-merriam-webster-system-1

[60] Reddy (2004) – Modelling and Analysis of Rail Grinding & Lubrification Strategies for Controlling Rolling Contact Fatigue (RCF) and Rail Wear

https://core.ac.uk/download/pdf/10884563.pdf

[61] Digital McKinsey (2018) – The rail sector's changing maintenance game

[62] V.A. Profillidis (2014) – Railway management and engineering

[63] Carter, F. W., The electric locomotive, Proc. Instn. Civ. Engrs., 221, 221 – 252, 1916

[64] Rail Engineering International, Edition 2008, Number 1 : Speno International SA – Rail grinding strategies for achieving optimum results

[65] U.S Department of Transportation, Federal Railroad Administration - Rolling Contact Fatigue: A Comprehensive Review – Final Report, November 2011

[66] AUTOMAIN (2013) – Augmented Usage of Track by Optimisation of Maintenance, Allocation and Inspection of Railway Networks. Project Reference: 265722, Research Area: SST.2010.5.2-1

[67] UIC CODE 519 - Method for determining the equivalent conicity

Appendices

Appendix 1 – Reference profiles Wheel A / Rail A combination - CONTACT

DMA Torino	Conicità equivalente coppia singola sala-binario EN15302	DMA

Nome file sala	**Wheel_A_EN15302**		
Data misura:	2000/01/01	Numero sala:	0
Km totali:	0.000000	Id. sala:	None
Tipo veicolo:	TEST	Posiz angolare prof:	
Id. Veicolo:	None	Sala motrice:	Undefined
Data ultima tornitura:		Profilo a nuovo:	Undefined
Km da ultima tornitura:	0.000000		
Commento:	Wheel A - EN15302		

Scartamento ruote:	1360
Scartamento interno:	1425.37

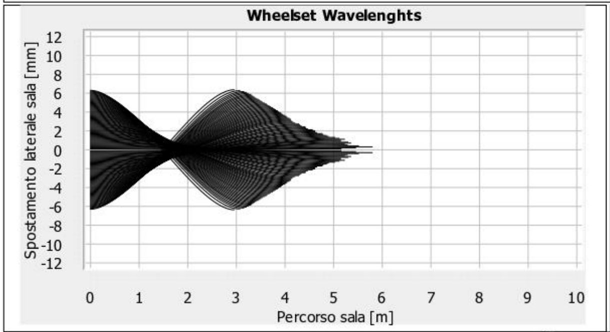
Lato destro		**Lato sinistro**	
Sh	27.98	Sh	27.98
Sd	32.68	Sd	32.68
Qr	10.96	Qr	10.96
R0	460.01	R0	460.01

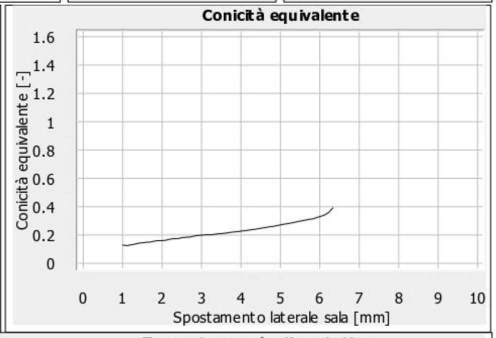
Steering index	0.000
RE:	0.000

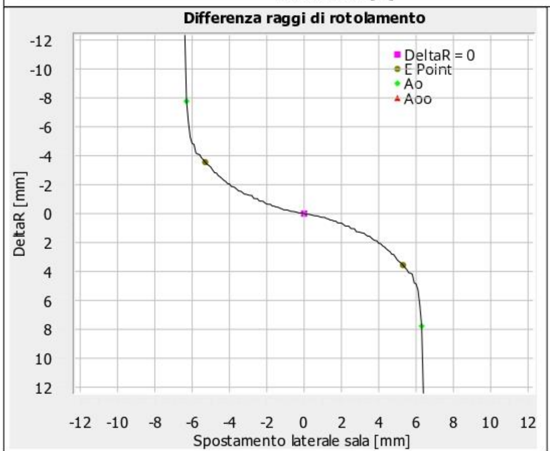
File profilo binario	**Rail_A_EN15302**		
Data misura:	2012/11/13	Inclinazione:	Undefined
Id. strumento:	Theoretical	Id rotaia sinistra:	2
Profilo nuovo:	Undefined	Id rotaia destra:	1
Linea:	None	Scart. binario:	1435.17
Tratta:	None	Posizione Km:	0.000000
Binario:	----	Curvatura 1/Km:	0.000000
Commento:	Teor. Track EN15302 - type A		

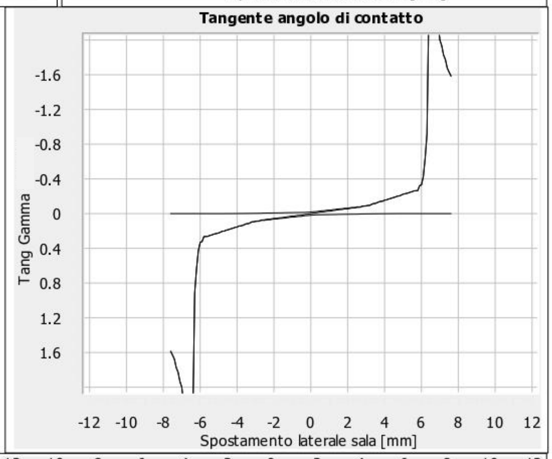
Scart. binario:	1435.17
Rotazione ruota in contatto:	Si

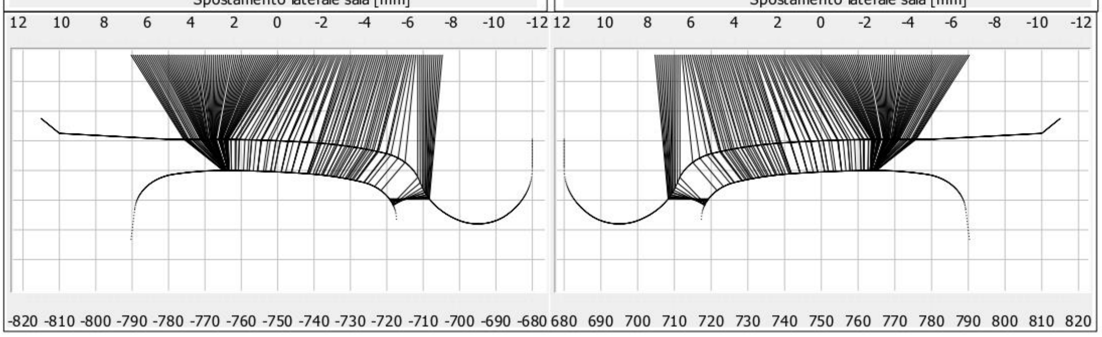
mm	Eq. Con.	mm	tg
1	0.129	-6	0.331
2	0.160	-4	0.142
3	0.199	-2	0.054
4	0.227	0	0.000
5	0.271	2	-0.054
6	0.330	4	-0.155
EN14363	0.199	6	-0.425











Appendix 2 – ORE S1002 worn wheel profile / UIC60 rail profile (1435 mm gauge, 1:20 cant)

DMA Torino	Conicità equivalente coppia singola sala-binario EN15302	DMA

Nome file sala	**S1002**		
Data misura:	2000/01/01	Numero sala:	0
Km totali:	0.000000	Id. sala:	None
Tipo veicolo:	TEST	Posiz angolare prof:	
Id. Veicolo:	None	Sala motrice:	NO
Data ultima tornitura:		Profilo a nuovo:	S1002
Km da ultima tornitura:	0.000000		
Commento:	Teor. profile S1002		

Scartamento ruote:	1360
Scartamento interno:	1425.05

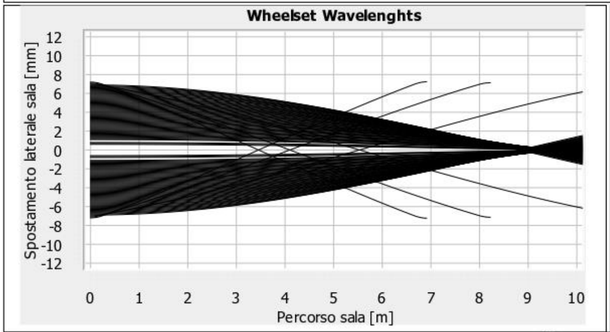
Lato destro		**Lato sinistro**	
Sh	27.98	Sh	27.98
Sd	32.53	Sd	32.53
Qr	10.81	Qr	10.81
R0	460.01	R0	460.01

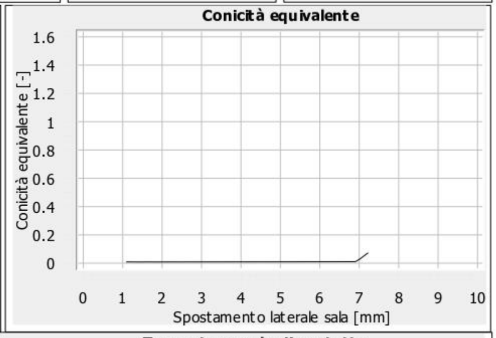
Steering index	0.000
RE:	0.000

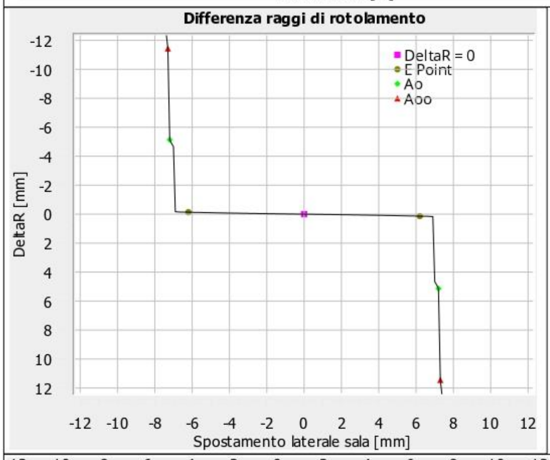
File profilo binario	**60E1_20**		
Data misura:	2012/11/13	Inclinazione:	1/20
Id. strumento:	Undefined	Id rotaia sinistra:	1.2
Profilo nuovo:	UIC60	Id rotaia destra:	1.1
Linea:	None	Scart. binario:	1436.93
Tratta:	None	Posizione Km:	0.000000
Binario:	----	Curvatura 1/Km:	0.000000
Commento:	60E1		

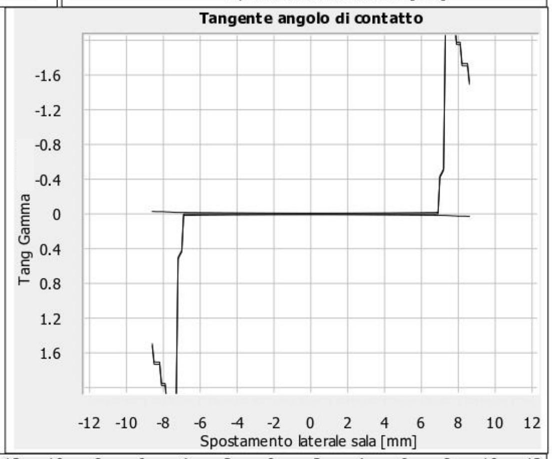
Scart. binario:	1436.93
Rotazione ruota in contatto:	Si

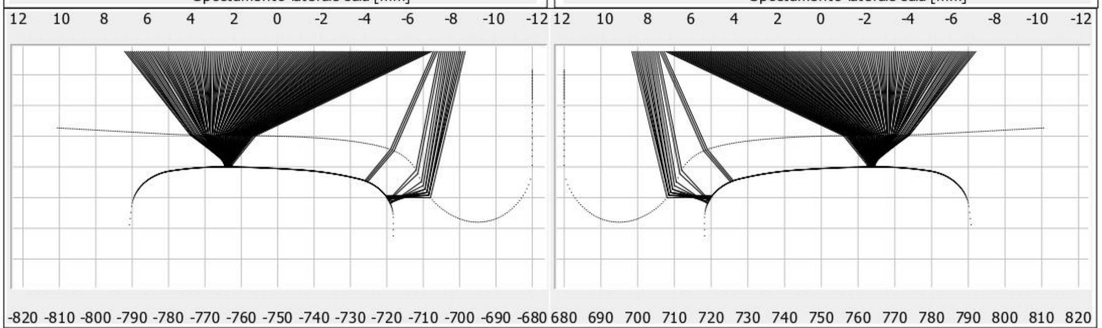
mm	Eq. Con.	mm	tg
1	0.009	-6	-0.000
2	0.009	-4	-0.000
3	0.009	-2	-0.000
4	0.010	0	0.000
5	0.010	2	-0.000
6	0.010	4	0.000
EN14363	0.009	6	-0.001











Appendix 3 - ORE S1002 worn wheel profile / UIC60 rail profile (1435 mm gauge, 1:40 cant)

DMA Torino	Conicità equivalente coppia singola sala-binario EN15302	DMA

Nome file sala	**S1002**		
Data misura:	2000/01/01	Numero sala:	0
Km totali:	0.000000	Id. sala:	None
Tipo veicolo:	TEST	Posiz angolare prof:	
Id. Veicolo:	None	Sala motrice:	NO
Data ultima tornitura:		Profilo a nuovo:	S1002
Km da ultima tornitura:	0.000000		
Commento:	Teor. profile S1002		

Scartamento ruote:	1360
Scartamento interno:	1425.05

Lato destro		**Lato sinistro**	
Sh	27.98	Sh	27.98
Sd	32.53	Sd	32.53
Qr	10.81	Qr	10.81
R0	460.01	R0	460.01

Steering index	0.000
RE:	0.000

File profilo binario	**60E1_40**		
Data misura:	2012/11/13	Inclinazione:	1/40
Id. strumento:	Undefined	Id rotaia sinistra:	1.2
Profilo nuovo:	UIC60	Id rotaia destra:	1.1
Linea:	None	Scart. binario:	1435
Tratta:	None	Posizione Km:	0.000000
Binario:	----	Curvatura 1/Km:	0.000000
Commento:	60E1 1/40		

Scart. binario:	1435
Rotazione ruota in contatto:	Si

mm	Eq. Con.	mm	tg
1	0.357	-6	0.467
2	0.221	-4	0.095
3	0.179	-2	0.064
4	0.160	0	0.000
5	0.183	2	-0.066
6	0.299	4	-0.095
EN14363	0.179	6	-0.511