Philipp Weiss, BSc

Maintenance Cost Comparison of Wheelsets for Metro Bogie Design Concepts

Master's Thesis

MSc

Production Science and Management

Graz University of Technology

Faculty of Mechanical Engineering and Economic Sciences

Institute of Industrial Management and Innovation Research

Univ.-Prof. Dipl.-Ing. Dr.techn. Christian Ramsauer

Graz, 2013

Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

Graz, 25.11.2013

……………………………….

(Signature)

Acknowledgment

I want to use this page to thank all the people who I worked together with and who supported me during the thrilling period of writing my thesis.

First of all I want to thank Friedrich Timmer and Kurt Woels from Siemens who made this Master's Thesis possible and provided guidance throughout the period. The same gratitude goes to Mario Kleindienst and Christian Ramsauer who supervised the thesis from the Graz University of Technology.

I also want to thank all colleagues in Northampton, UK and Graz, Austria who were happy to help with their technical expertise. Last but not least many thanks to my family and my lovely girlfriend Emma who keeps me grounded at all times.

Abstract

This Master's Thesis assesses the maintenance cost implications associated with newly developed metro bogie design concepts. The impact of wheelset maintenance on life cycle costs is investigated in detail.

In the railway industry, maintenance costs of bogies and especially their wheelsets accumulate during their life cycle to several times the purchasing price. Customers consider life cycle costs, which include maintenance, as important decision criteria for awarding train purchasing contracts. Over the years, Siemens has created various train and bogie concepts as part of a feasibility study. The thesis shall assist in the process of identifying the most suitable bogie design concept. A maintenance cost benchmark of wheelsets and gearboxes enabled a recommendation to be made at the end of this work.

An initial study at Siemens Bogie Plant Graz provided the technical background of the concepts and a placement at Siemens Rail UK enabled information to be gathered from London Underground and from maintenance experts.

Firstly, the thesis provides theoretical background on the British railway industry and covers the theoretical background of maintenance and life cycle costing. Then maintenance plans for a period of 40 years were analysed and implemented into life cycle cost models. The first cost sensitivity analysis identified the largest cost drivers to be the wheel exchange and gearbox overhaul. The thesis therefore concentrated on the wheel life cycle prediction and gearbox maintenance cost benchmark. Still, the cost models required numerous input parameters and customer specific field data. Gathered field data from various visits to London Underground support the research with the necessary information on the train operating environment.

The wheel life cycle prediction turned out to be challenging. With the conducted analysis it was possible to identify wheel life potential by assessing the design variants with a parameterised excel tool. Acquired estimations were compared with similar underground projects and actual wheel life data from the London Underground. A similar benchmarking approach was followed for the gearboxes and showed their cost position compared to reference projects.

Actual data from London Underground was implemented and life cycle cost models were run with and without discount rates. The results show the great impact of the costing method used. Additionally, wheelset overhaul scenarios were implemented to show the financial impact of different maintenance strategies. A final maintenance cost benchmark allowed a cost ranking to be obtained for the design concepts and the further discussion of their maintainability.

Kurzfassung

Diese Masterarbeit beschäftigt sich mit der Instandhaltung und den Instandhaltungskosten von vier unterschiedlichen Radsatzbaugruppen neu entwickelter Siemens U-Bahn Drehgestellkonzepte. Genauer wird dabei der Kosteneinfluss der Radsatzinstandhaltung auf die Lebenszykluskosten betrachtet.

Im Bereich der Schienenfahrzeuge fallen bei der Instandhaltung von Fahrwerken und deren Radsätze Kosten an, die den Kaufbetrag um ein Mehrfaches übersteigen. Diese sind Teil der Produktlebenszykluskosten und somit ein wichtiges Entscheidungskriterium bei der Vergabe von neuen Aufträgen. Deswegen ist es im Interesse von Siemens die kostengünstigste Variante zu ermitteln und das Ziel dieser Arbeit den Kosteneinfluss der Radsätze zu betrachten. Nach abgeschlossener Analyse war es möglich eine Empfehlung bezüglich der kostengünstigsten Radsatz- und Getriebebaugruppen abzugeben und das Ergebnis kann somit als Hilfestellung für eine Variantenentscheidung verwendet werden.

Einer Analyse der Konzepte im Siemens Drehgestellzentrum Graz folgte ein mehrmonatiger Aufenthalt bei Siemens Rail in Northampton um Instandhaltungserfahrungen und Felddaten der Londonder U-Bahnen in die Arbeit einfließen lassen zu können.

Zu Beginn wurden auf die englische Eisenbahnindustry, die potentiellen Instandhaltungskonzepte und Methoden zu Lebenszyklusrechnungen eingegangen. Präventive Instandhaltungspläne über einen Zeitraum von 40 Jahren wurden für alle vier Konzepte kreiert und in die erstellten Kostenmodelle eingearbeitet. Eine erste Berechnung zeigte die größten Kostenfaktoren, welche als Radstandzeit und Getriebeinstandhaltung identifiziert wurden. Beim weiteren Vorgehen zur Verbesserung der Kostenmodelle wurde daher genauer auf die Abschätzung eines potenziellen Radtauschintervals eingegangen und ein Getriebeinstandhaltungskostenvergleich erarbeitet. Darüber hinaus wurden für die Kostenmodelle zahlreiche Eingangsparameter benötigt, welche durch Besuche von London Underground Instandhaltungseinrichtungen und Interviews mit Instandhaltungsexperten über Felddaten erhoben wurden.

Die Vorhersage der Radstandzeit stellte sich als anspruchsvoll heraus. Es war jedoch möglich eine potentielle Lebensdauer der Räder abzuschätzen und mit den erreichten Werten der Londoner U-Bahnen zu vergleichen. Auch die Getriebeüberholung wurde mit Referenzprojekten verglichen und ihre Kostenposition im Vergleich dargestellt.

Schlussendlich wurden Erkenntnisse und Felddaten in die Kostenmodelle implementiert, welche anschließend mit und ohne Diskontierungssatz ausgeführt wurden, wobei die berechneten Ergebnisse eine große Sensitivität bezüglich der gewählten Methode zeigen. Des Weiteren wurden verschiedene Überholungsstrategien simuliert und resultierende Kosten verglichen. Ein abschließender Benchmark zeigt wie Instandhaltungskosten der Konzepte zueinander stehen und erlaubt eine Empfehlung zur Auswahl des geeignetsten Radsatzkonzepts.

Table of contents

1 Introduction

In the railway industry, maintenance costs of bogies will accumulate to several times the purchasing price within their lifecycle. Customers consider life cycle costs, which include maintenance, as important decision criteria for awarding train purchasing contracts to bidders. Maintenance regimes can alter within the legal framework and are influenced by the operational environment, operator experience, available resources and the maintenance strategy. The wheelset assembly, which includes components such as the gearbox is one of the main cost drivers in bogie maintenance and will be the focus of this thesis.

A placement at the Siemens bogie plant in Graz followed by a placement at the Siemens traincare facility in Northampton provided an understanding of the LCC requirements from both a manufacturers' point of view and also from an operational perspective. This provided the opportunity to include and match operator & maintainer knowledge, expert opinions and customer requirements in the wheelset benchmark. This chapter introduces Siemens Rail Systems and describes the aim and approach of the thesis.

1.1 Siemens Rail Systems

With its rail division, Siemens as a company is one of the world's largest developers and manufacturers of metros, trams, trainsets, high-speed trains and locomotives. The plant in Graz is Siemens' world competence centre for bogie manufacturing.

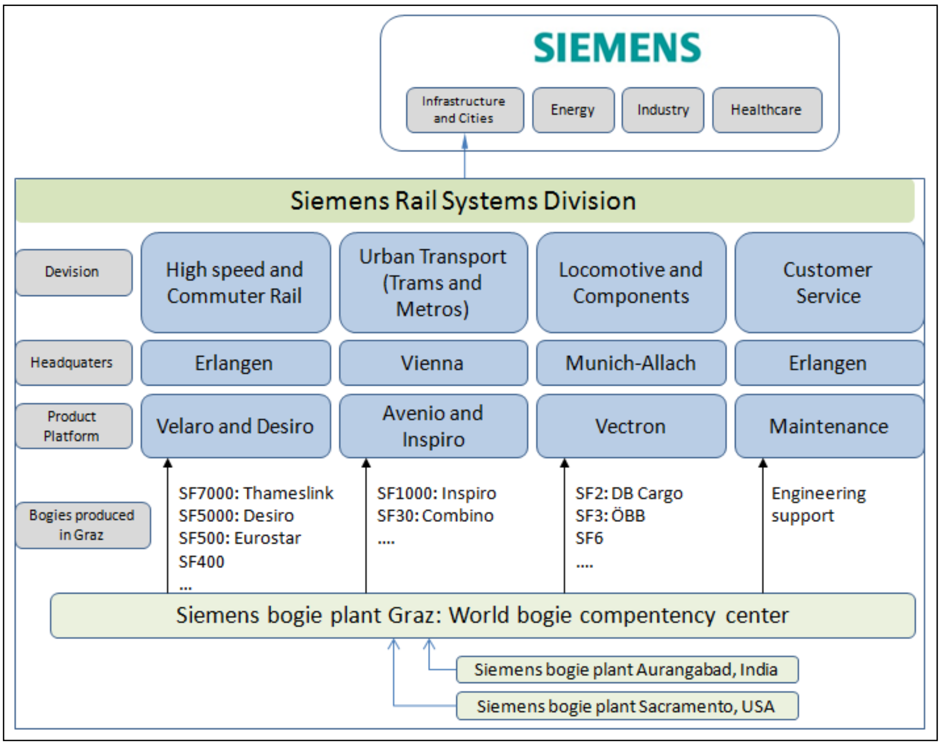


Figure 1: Structure of Siemens Rail Systems and products[1]

[1] Siemens (2013)

Bogies are mounted under the train and support the whole train body on the rails. The design specifies the dynamic drive behaviour and which components are installed. The wheelset is one of its main assemblies and is the connection between rails and the bogie.

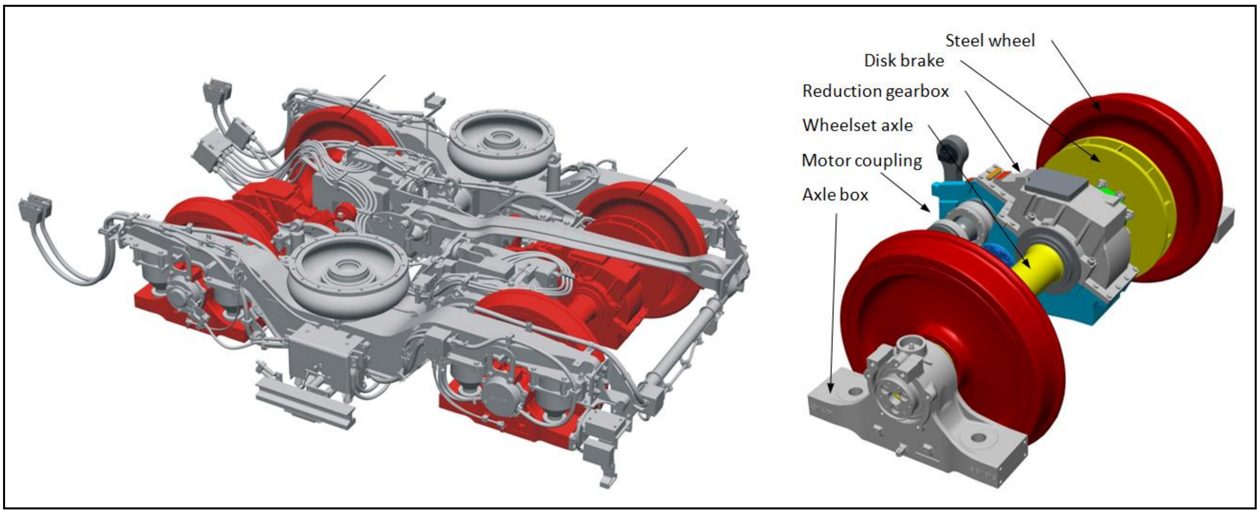


Figure 2: Metro bogie with highlighted wheelsets[2]

The wheelset can either be driven (motor wheelset) or just support the bogie (trailer wheelset). The definition of a wheelset is specified in EN 15313:2010 and is officially referred to as the wheelset axle and wheels mounted. Due to the common use of the term, an extension of the definition can be found for the whole assembly that also includes axle bearings, brake discs and the part of the drive that is mounted on the wheelset. The maintenance of a wheelset mostly requires considering the whole assembly rather than specific parts in it.

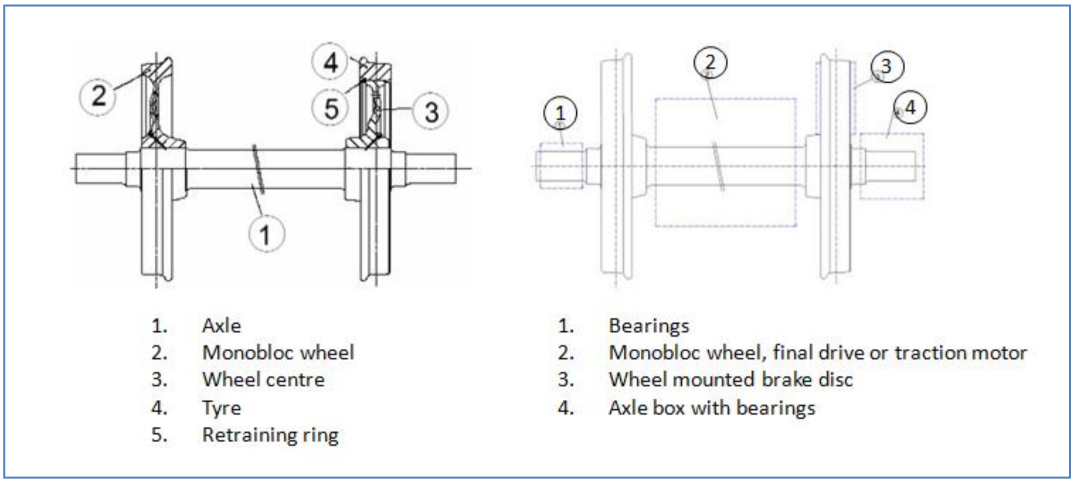


Figure 3: Wheelsets and its components according to DIN EN 15131[3]

The picture above shows different types of designs including a monobloc wheel compared to an alternative wheel assembly. The position of the axle bearings can be either behind the wheels (inboard) or outside the wheels as shown above.

[2] Referring to the wheelset maintenance manual of metro "Inspiro Warszawa" motor wheelsets
[3] European Committee for Standardisation (CEN) (2010, p. 15)

This thesis was initiated in order to find the most cost effective of the bogie design concepts, which were developed at the Siemens bogie plant in Graz. Transport for London (TfL) is a customer of Siemens and it is possible that new trains will be ordered from Siemens in the future.

London Underground Limited (LUL), a part of TfL has published an official tender notice on the European tender homepage as follows:

"London Underground Limited (LUL) is planning the upgrade of the Bakerloo, Piccadilly, Waterloo & City and Central lines (and possibly others) as part of the Deep Tube Programme (DTP)."[4]

According to Siemens' internal estimations, the winner of this contract, which is to be awarded in late 2015, will have to supply up to 3,400 Deep Tube Cars[5]. Siemens is an OEM that has the capacity to handle this contract volume and thus has been preparing for the upcoming tender over the past two years. The Siemens Bogie Plant in Graz developed four bogie design concepts in a feasibility study and created life cycle cost (LCC) models for each of them. Various train concepts implementing these bogie designs have been created at Siemens' Vienna plant where LCC models of sub assemblies are combined in an overall model to show the full impact of life cycle costs for a whole train.

The underground trains will have a planned life cycle of 40 years and the costs caused due to maintenance over this period are significant criteria for contract awards. The thesis investigates these maintenance costs for each of the concepts and focuses on wheelsets and gearboxes.

Previously created life cycle cost models at Siemens include assumptions about the costs, maintenance periods and operational conditions of London Underground. At the concept project stage, the prediction of wear and the lack of knowledge about customer's maintenance strategies made it necessary to make these initial guesses.

1.2 Aims of research

The aim behind this thesis was to create an improved LCC model which includes typical customer specifications and also to implement the best practice for maintenance cost comparison. References to the train operating environment were necessary and gathered field data was hoped for to increase the accuracy of cost models. Various visits to London Underground facilities were planned and other reference projects were provided to improve these models.

Identifying the biggest cost factors was a requirement in the beginning in order to define priorities for further component specific analysis. A known driver for wheelset maintenance is the mileage life of wheels before their renewal is necessary. It is very difficult to accurately predict this life because wheel wear is influenced by a large number of parameters (track condition, curve sizes, axle loading etc.). Data for these parameters shall be gathered as far as

---

[4] London Underground Ltd. (2013)
[5] Referring to internal report of Siemens

possible and the lifetime of wheels estimated. Reference to the experiences of the Siemens Metro platform will be made for this purpose.

Maintenance processes, involving material and labour costs, synchronicity of intervals and London Underground strategy considerations over 40 years form the basis for the accumulation of life cycle costs. This work will also show what sort of influence the exchange intervals of components have on the synchronicity of maintenance and the overall life cycle costs.

The theoretical approach will be completed with the practical experience from Siemens UK maintenance experts and London Underground experience. Comparisons with other metro projects and field data shall support the outcome. Various visits to Siemens depots and London Underground premises shall provide this field data for the thesis. As a result the views from engineering, LCC, wheelset and maintenance experts were used to provide the data for the thesis.

Summary of main aims:

- Maintenance cost benchmark of wheelset design concepts and their gearboxes
- Identification of appropriate methods for the benchmark and their application
- Field data gathering and implementation in life cycle cost models
- More detailed consideration of the wheel life cycle and gearbox maintenance

1.3 Approach and overview

The approach and structure of this work is explained by outlining the content of each chapter. Initially, the British railway industry, with its stakeholders, norms and standards will be briefly explained in order to create a common understanding. Differences to the government run London Underground organisation, with its own regulations, are then discussed.

Chapter 3 describes the necessity of maintenance and different approaches that can be introduced, considered from an OEMs viewpoint as well as from a maintainer's perspective. Required maintenance will be explained specifically for wheelsets and maintenance plans then derived from it. Further, the context between life cycle costs and maintenance will be established from a theoretical point of view. This includes life cycle cost models, different costing methods and the related theoretical background.

Chapter 4 presents the bogie design concepts to be compared and discusses their features. The major cost drivers are derived and research questions defined to set the basis for the further work in more detail. London Underground premises were visited several times as well as Siemens maintenance facilities and suppliers. Field data gathered is presented and the bigger picture of London Underground maintenance strategy described.

Chapter 5 focuses on particular wheelset components and discusses wheel wear and gearbox maintenance. Various approaches were implemented to predict a possible wheel life cycle and are compared with LU data. Further to this, gearboxes are benchmarked and remaining wheelset components analysed.

Chapter 6 will show the results of applied cost models. Different methods of life cycle costing are compared and the impact of altered overhaul periods shown in various cost scenarios. Results will be visualised and a final recommendation about a concept to choose is given in the final conclusion.

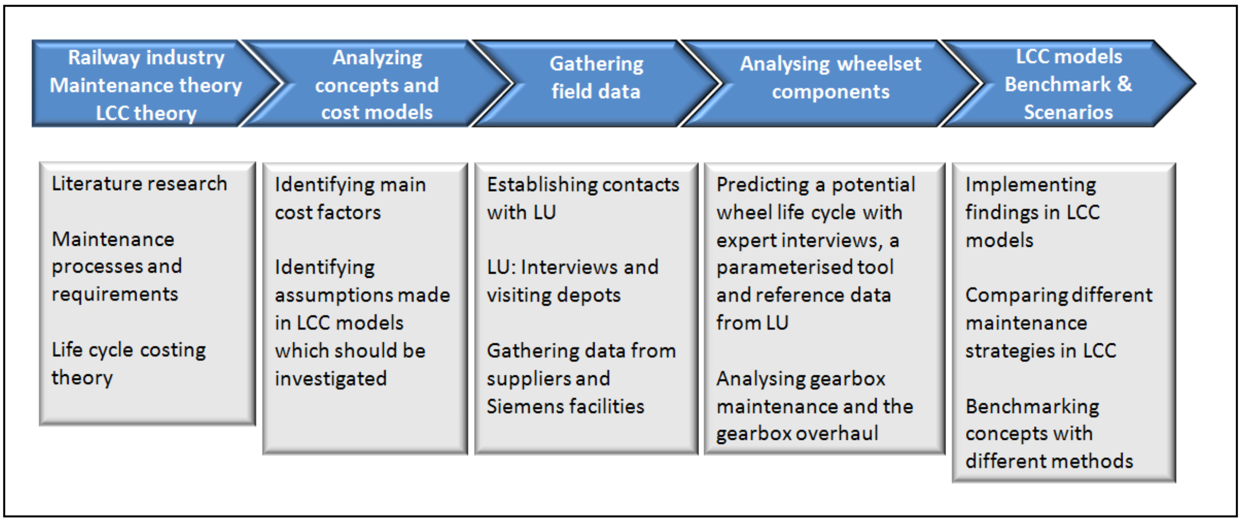


Figure 4: Procedural stages of thesis

Identifying, verifying and describing the most important cost factors will help to optimise the upcoming offers made to customers. Analysing influencing factors such as the wheel life cycle and the gearbox maintenance in context with the train operating environment will provide the necessary background for a variant decision of wheelset designs.

How topics are related is shown in an overview in the form of a mind map below and should provide an insight into involved content and chapters.

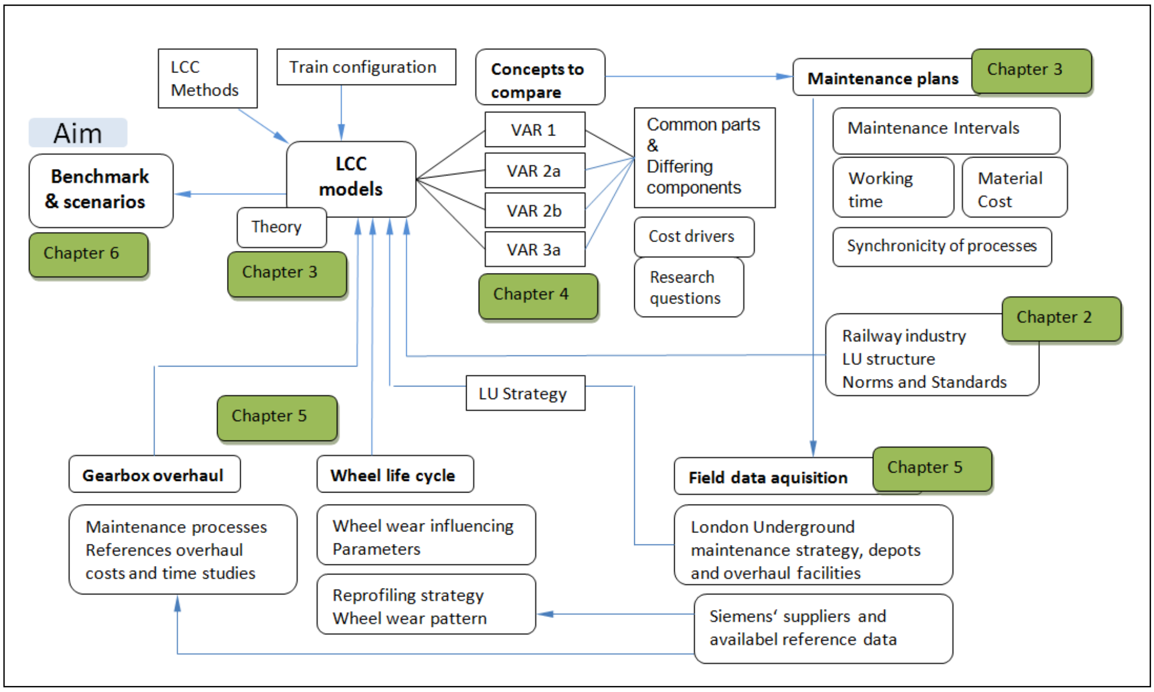


Figure 5: Overview and interaction of thesis content

2 UK Railway Industry and the London Underground

The British railway is different to those on mainland Europe. The bigger picture, involved parties, norms and standards will be covered to give the broad basis for investigating London Underground's particularities. Following this, on LU's organisation, tube lines and its maintenance approach will be introduced.

2.1 Mainland railway

Maintenance of rolling stock is tied to norms and standards in order to ensure passenger safety. Thus it is necessary to understand the railway industry in the UK before considering maintenance costs in more detail.

The state owned railway industry was privatised in 1994, which resulted in the distribution of tasks across private companies. This chapter shows an overview of involved parties and maintenance agreements in the UK. Subsequently, the environment of London Underground will be discussed in relation to it.

2.1.1 Parties involved

The parties commonly involved in the mainland railway industry can be seen here.[6]

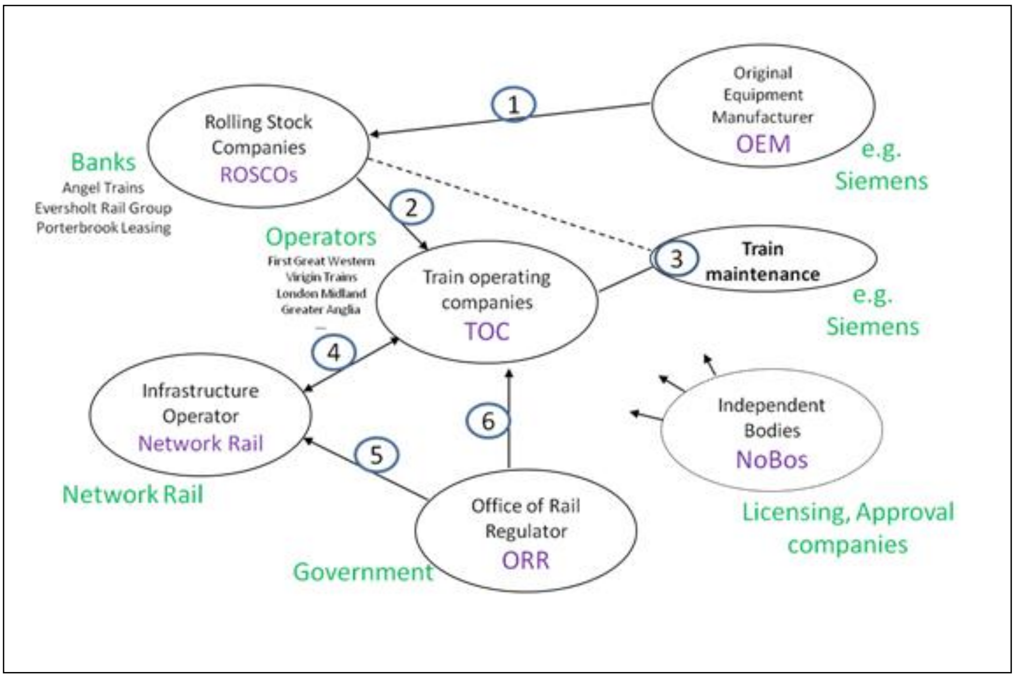


Figure 6: Typically involved parties in the British mainline railway industry (own illustration)

Rolling Stock Companies (ROSCOs) are banks that own trains and receive (1) new rolling stock from the Original Equipment Manufacturer (OEM). The office of rail regulation states that at the moment there are three leasing companies in the UK: "*Angel Trains Ltd., Eversholt Rail Group*

[6] Department for Transport (2012)

and Porterbrook Leasing Company Ltd." Existing passenger trains on the British market are from the following OEMs: "*Alstom Power, Bombardier Transportation, Hitachi Europe Ltd and Siemens Transportation Systems Ltd*."[7]

As banks don't operate trains they lease (2) them to Train Operating Companies (TOCs). According to the Association of Train Operating Companies (ATOC) there are currently 24 train operating companies in the UK.[8] The maintenance responsibilities of operated trains are specified in leasing contracts. Various types of maintenance agreements (3) are shown on the next page.

Network Rail owns national track routes and stations and imposes access charges to train operating companies. Network Rail itself is a private company that is regulated (5) by the government through the Office of Rail Regulation (ORR). The ORR is generally responsible for health and safety issues and is shaped by UK and European legislation.[9] Additionally there are independent companies and organisations called Independent Notified Bodies (NoBos) that are notified for approval and licensing issues.

The next subchapter was worked out with Siemens maintenance specialists (Kings Heath Traincare Facility in Northampton, UK) and shows that various contractual arrangements are possible for the maintenance responsibility of passenger trains.

2.1.2 Different forms of maintenance lease agreements

Three different forms of maintenance lease agreements will be explained. They are agreed on between the train owner and train operator and optionally include external partners. Outsourcing of maintenance functions normally requires a long term perspective. Outsourcing maintenance is most effective with new vehicles, when the manufacturer is contracted to take over the task. The advantage is that the OEM already understands major systems and normally has established relationships with suppliers of components and systems.[10]

Maintenance Agreement I

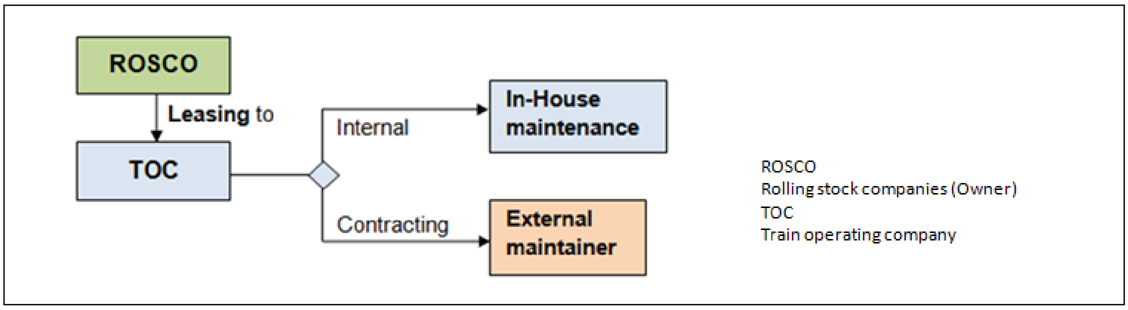


Figure 7: Maintenance responsibilities with the TOC ("Dry leasing") (own illustration)[11]

[7] Office of Rail Regulation (2012)
[8] ATOC (2013)
[9] Office of Rail Regulation (2013)
[10] Etwell (2001, p. 72f)
[11] Referring to Siemens maintenance experts, 05/2013

In this agreement the train operator is fully responsible for all maintenance issues and decides whether he can do the maintenance himself or wants to contract an external supplier. The TOC makes the decision for all maintenance related activities.

Maintenance Agreement II

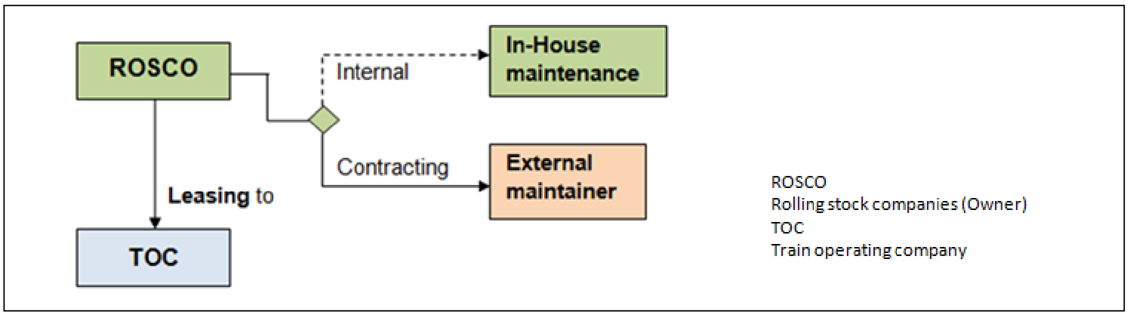


Figure 8: Maintenance responsibilities with the ROSCO ("Wet leasing") (own illustration)[12]

In constellation II the train owner keeps the responsibility for maintenance and decides whether it can be done internally or should be contracted to an external supplier. ROSCOs are banks and involvement with external maintainers is most likely.

Maintenance Agreement III

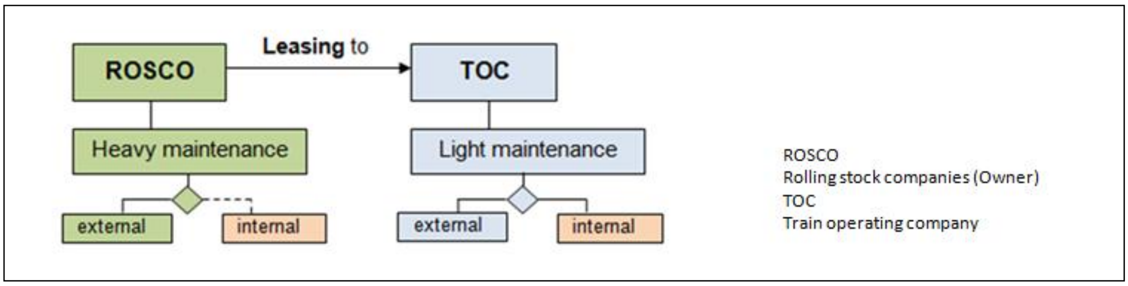


Figure 9: Shared maintenance responsibilities ("Soggy leasing") (own illustration)[13]

In arrangement III the train maintenance is divided and shared between the train owner and the train operator. The ROSCO has the responsibility and management of major repair works and overhauls. The TOC takes on all work that can be done in its depots or be transferred to its suppliers. Light maintenance refers to work that has to be done more frequently and includes visual inspections, measurements, cleaning and so on.

2.1.3 Norms & Standards

Norms and standards are in place to ensure a common understanding of safety, maintenance and procedures across the railway industry. This mostly includes minimum requirements for safety to control risk that is brought into the rail system. European Standards are in place to set a common engineering standard across countries and are slightly modified for specific countries. This modification is then indicated by, for example BS EN xxx for British European Standards or DIN EN xxx for German European standards. In the UK Railway Group Standards

[12] Referring to Siemens maintenance experts, 05/2013
[13] Referring to Siemens maintenance experts, 05/2013

are the most important standards and two, later required, references related to maintenance are shown in the table below.

Railway Group Standard RSSB, RGS online		
Norm and Status	Title	Description
GM/RT2004 **Issue 5, June 2012**	Rail Vehicle Maintenance	How to achieve conformity to standards with the maintenance plan and documentation.
GM/RT2466 **Issue 3, February 2010**	Railway Wheelsets	Requirements for the design, manufacture and maintenance of wheelsets and their components.

Table 1: Railway Group Standards, RSSB (Railway Standard and Safety Board)[14]

A more comprehensive collection of Rail Group Standards can be found in the appendix. Additionally there are Rail Industry Standards in place that provide "guidance notes" and "codes of practise" for the industry. London Underground defines its own standards but they are closely related to the standards above described.

2.2 London Underground

London Underground Limited (LUL) is part of the Transport for London (TfL) and run by the government. This year it is celebrating its 150th anniversary which means it is one of the oldest underground operations in the world. LU consists of 11 lines and transported 1171 million people in 2012, accumulating 72.4 train kilometres. The tunnel proportion in the network is only around 45% and the average train speed is 33 km/h including station stops. [15]

A policy called "freedom of information" is in place and enables the public to request information as the operation is funded by tax money.

Line	Group	Trains required	Depots	Stations
Jubilee	JNP	49	Stratford Market	27
Northern	JNP	91	Golders Green / Morden	50
Piccadilly	JNP	78	Northfields / Cockfosters	53
Bakerloo	BCV	33	Stonebridge Park	25
Central	BCV	76	Ruislip/Hainault/White City	49
Victoria	BCV	37	Northumberland Park	16
District	SSR	76	Ealing Common / Upminster	60
Metropolitan	SSR	48	Neasden	34
Circle / Hammersmith & City	SSR	32	Hammersmith	36 / 29
Waterloo & City	SSR	5	Waterloo	0

Table 2: Overview of operated lines with trains, depots and stations

One who has travelled with the tube during peak time knows that the system is working at its full capacity. Some of the trains are more than 40 years old and will be subject to the upgrade plan shown below.

[14] RSSB (2013)
[15] Transport for London (2013a)

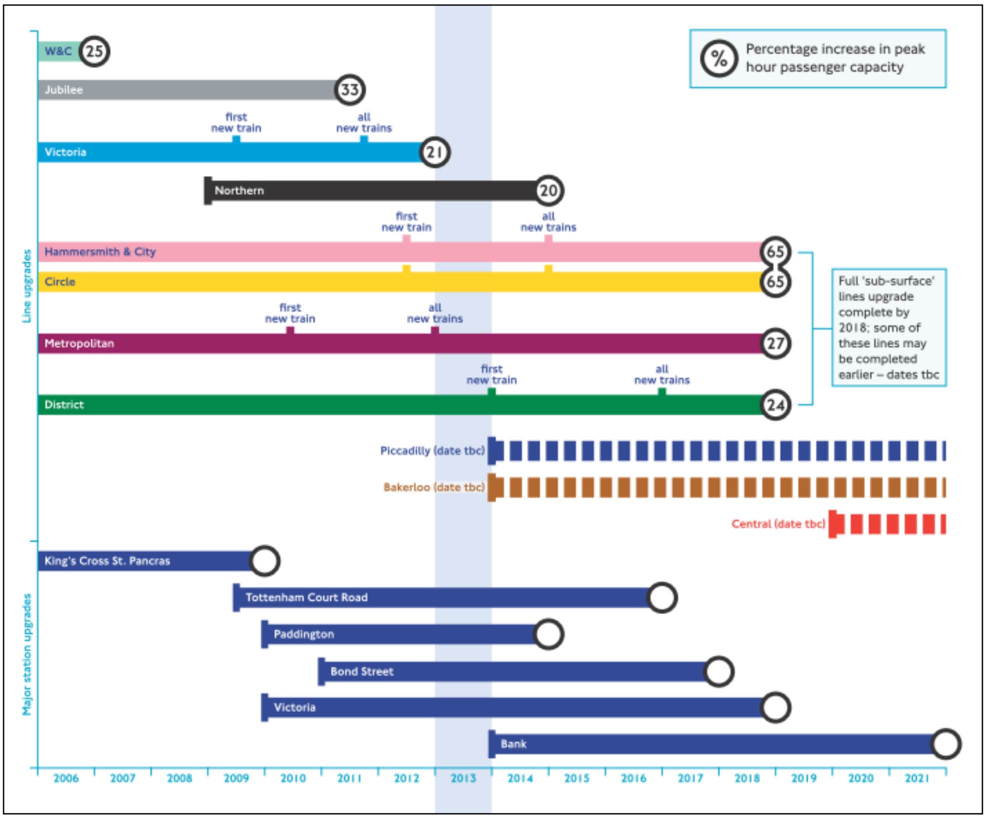


Figure 10: London Underground upgrade plan[16]

The proposed Siemens design concepts could be offered for this upgrade plan and trains would be used for the Piccadilly and Bakerloo line. The upgrade plan could further include a purchase of trains for the Central line.

2.2.1 LUL Organisation 2013

The LU organisation is big and shall be briefly explained to show how and from which departments the maintenance of tube trains is managed.

[16] Transport for London (2013b)

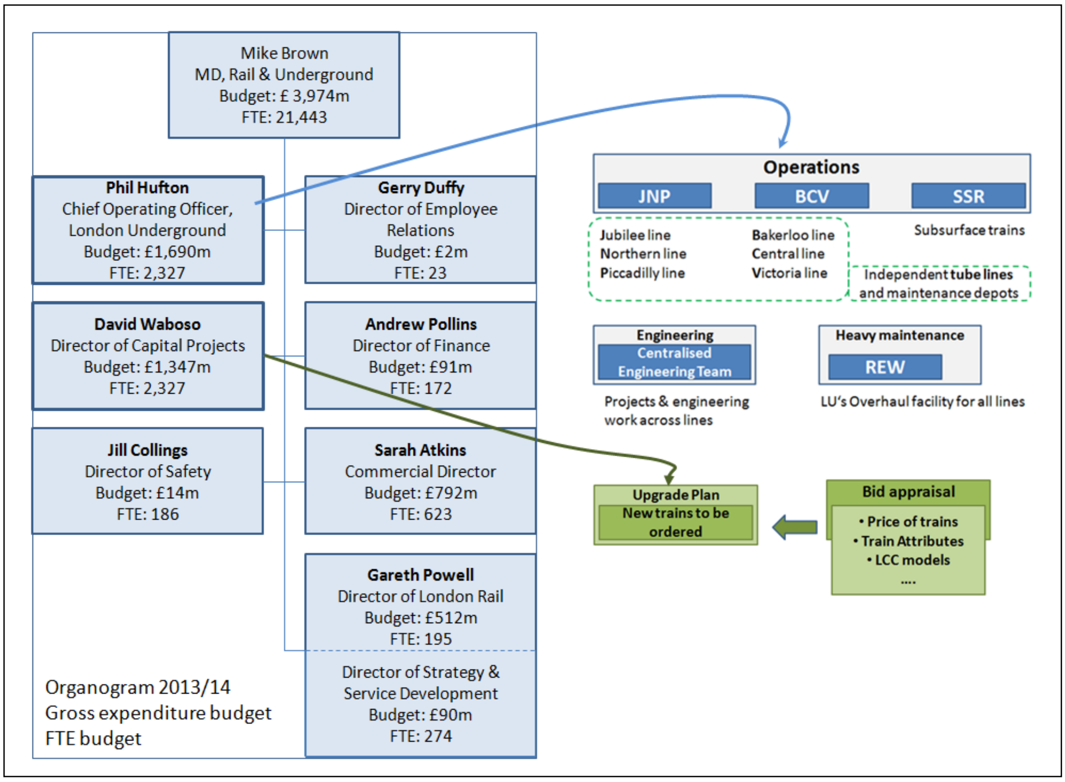


Figure 11: LU's organisational chart 2013/14[17]

Historically the tube lines were split up into the groups JNP/BCV/SSR as different companies were contracted for maintaining the trains. Metronet was responsible for BCV and Tubelines was responsible for the maintenance of JNP. Neither organisation exists anymore but are embedded in the structure of the London Underground organisation.

The only line where the provision of trains is placed with a third party is the Northern line. All other 7 tube lines are owned and run by London Underground.

2.2.2 LUL Norms & Standards

A safety case is the basis for norms and standards as, with it, an organisation demonstrates how it can ensure safe and sustainable operation. The LUL railway safety case was accepted by "Her Majesty's Railway Inspectorate" (HMRI) in 1996. But LUL also uses Network Rail infrastructure, which is subject to Rail Group Standards (RGS) and therefore had to submit a safety case to them as well.[18]

How LU has structured its 3 level train maintenance standards is shown in the next figure.

[17] Transport for London (2013c)
[18] Batchelor (1997, p. 49ff)

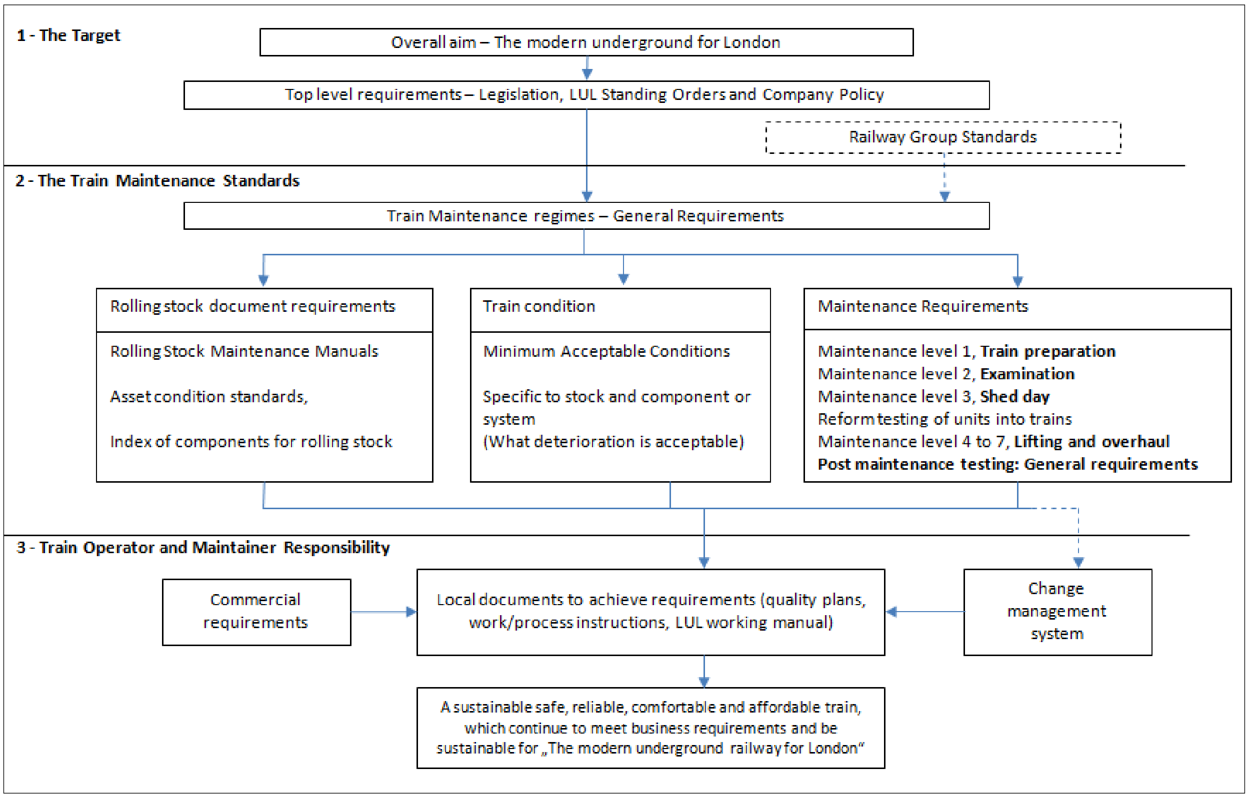


Figure 12: Structure of LUL's Train Maintenance Standards[19]

This general overview shall now be narrowed down to wheelset maintenance. An enquiry was made to receive wheelset standards via the freedom of information online tool and LU's wheelset maintenance requirements are stated here.

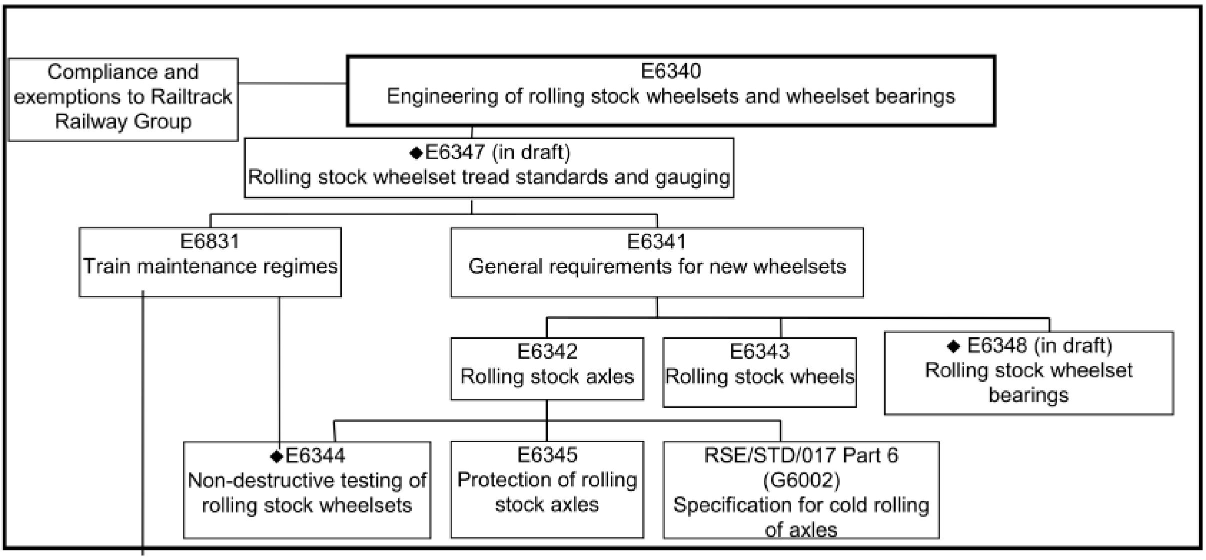


Figure 13: London Underground specific wheelset standards[20]

[19] Holmes and Dymott (1997, p. 66)
[20] London Underground Ltd. (2006p.10)

2.3 Summary

This chapter has provided a short overview of the railway environment in the UK and pointed out the differences to LU as it is a government owned service. A reference to norms and standards related to maintenance has been made. This is relevant to LCC models as maintenance procedures are specified accordingly to the legislative boundaries. The clear understanding of different LU lines, depots and the shared overhaul centre “REW” is essential for the following models and the field data acquisition.

The next chapter discusses the maintenance topic and the related costs in more detail.

3 Maintenance and Maintenance Costs

The previous chapter showed that maintenance in the railway industry is framed by norms and standards. The proposed design concepts will have a life cycle of around 40 years, which is a standard value for rolling stock. Maintenance costs during this time are significant and safety standards must not decrease over the years. After a brief introduction to maintenance and its various approaches a more detailed description of wheelset maintenance will be given. In the end of this chapter a theoretical maintenance plan is presented, which will subsequently be used in the cost models. These cost models require a defined structure and an implemented costing method. The theoretical background related to maintenance costs will therefore be described and the used tool introduced.

3.1 Introduction to maintenance

Definition of maintenance: "*the combination of all technical and administrative actions, including supervision actions, intended to retain a product in, or restore it to, a state in which it can perform a required function (IEC 60050(191))"*[21] In German literature the same definition can be found in DIN 31051.

History of maintenance: Until the beginning of the 19th century maintenance came into use as the reestablishment of something that had failed. But the industrial revolution created more and more production facilities and thus maintenance became relevant. Initially it was in place to repair broken machines as quickly as possible in order to sustain high production output. This reactive approach was then developed to a more preventive one to protect devices from failing which included inspections. Further developments brought maintenance into context with equipment measurements and related condition based actions. With the development of computer technologies in the 1980s it was included into life cycle analyses, simulations and planning processes. The latest developments have been towards knowledge based maintenance and proactive maintenance. Nowadays maintenance is often seen as part of the value creation chain itself and strongly related to environmental and safety topics.[22]

3.2 Classification and types of maintenance

Everyone who implements maintenance on a product or equipment will have to face the decision which approach fulfils the purpose best. Mobley[23] offers a comprehensive choice of maintenance approaches and states that in the production industry the run to failure and preventive maintenance are the most common.

[21] British Standard (2010, p. 9)
[22] Strunz (2012)
[23] Mobley (2002)

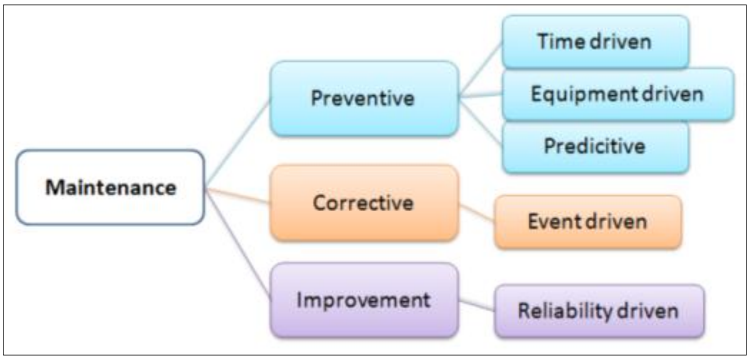


Figure 14: Classification of maintenance[24]

Preventive maintenance is either based on a fixed time or distance interval; the condition of equipment or based on forecasts. In railway engineering the OEM initially specifies preventative maintenance regimes in manuals. Preventive maintenance is closely related to statistics as failure probability considerations are involved before intervals are set. The most common description of failure is the bathtub curve. This curve describes that initial failures are high and once these defects are eliminated the curve flattens out until wear becomes critical. In addition, modern technology often gives a choice between cost and failure rate regarding the equipment in use.

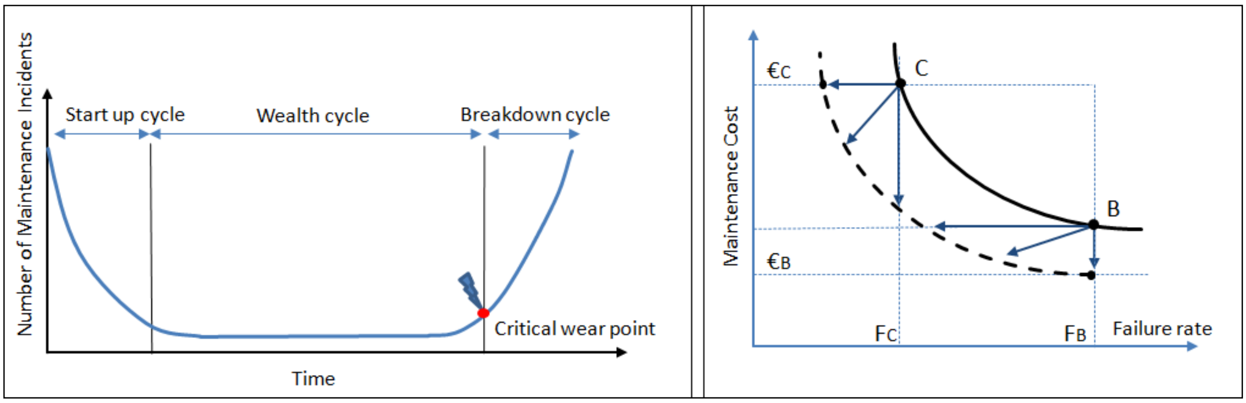


Figure 15: Bathub curve[25] (left) and cost/failure rate choice[26] (right)

One of the choices to make would be to increase preventive maintenance intervals and accepting the risk of a higher failure rate. This optimises costs considering the amount of work required but has to be closely analysed if safety or down time is at risk.

Day and Scappaticci[27] suggest that preventative maintenance is most effective if the equipment suffers from a strong age related failure mode in a relatively short time span. Examples are given with fatigue and corrosion of components.

Predictive maintenance is closely related to preventive maintenance and involves measurements made on parts or systems. These measurements are then used as indicators for wear and maintenance requirements. Predictive maintenance is either statistically based or

[24] Mobley (2002, p. 413ff)
[25] Levitt (2003, p. 38)
[26] Morris (1997, p. 16)
[27] Day and Scappaticci (2001, p. 90f)

condition based. Mobley[28] points out that vibration monitoring, thermography, tribology, visual inspections, ultrasonic tests and electrical testing are methods used for predictive maintenance approaches. An example in rolling stock applications is taking regular oil samples from a certain amount of gearboxes on the train and using the metal content measured as an indicator for the condition of bearings. The right sample sizes as well as intelligent and reliable data are the key. Another railway application is “RailBam” which is a stationary device beside rails that listens to axle bearing noises and informs the operator once a frequency indicates worn axle bearings.

Corrective maintenance is the unplanned work that has to be done after a part of a system has failed or lost parts of its functionality in order to restore it. These repairs or part/system changes are subject to a reactive nature and problem solving. Reactive maintenance on its own is the most costly variant of keeping a system running as it only takes action once the failure has occurred. In railway corrective maintenance handles failures that cannot be prevented even if other types of maintenance are executed. In most cases a certain failure rate is always part of a system and statistical parameters like the MDBF (mean distance between failures) of a component indicates how often corrective maintenance has to be done. An example can be found in high speed rail applications where hot axle box detection systems measure the temperature of axle bearings and stop the train once a failing bearing is detected.

Improvement maintenance is the approach of changing a system or component in order to increase its reliability, productivity, and cost or safety performance.

Drivers for maintenance are wear, material aging and corrosion of parts and systems. In the production industry maximising output, minimizing energy usage and optimising resources are the main reasons to invest in maintenance. One way of measuring its success is measuring overall equipment effectiveness (OEE). This means maintenance is in place to reduce breakdowns, reduce down time and improve the equipment efficiency. Rolling stock maintenance on the other side is more concerned about providing a high availability and reliability of trains while complying with safety standards. Passenger safety has to be ensured at all times and down time reduced for a good service and customer satisfaction. The main metrics used are availability and reliability concerning the fleet performance. These parameters will be at the forefront of the London Underground tender for renewing their trains. In the end every train owner still wants to optimise the economic output of its asset, which is why the total cost of ownership (TCO) is one of the strongest decision criteria for purchases.

Using an example of a rotating machinery Day and Scappaticci[29] state that in terms of cost reactive maintenance is the most costly approach and that proactive maintenance is the most cost effective.

3.3 Maintenance of railway vehicles

Maintenance on railway vehicles is sensitive and the European Standard EN 50126 defines involved types of maintenance as follows.

[28] Mobley (2002, pp. 99-112)
[29] Day and Scappaticci (2001, p. 89f)

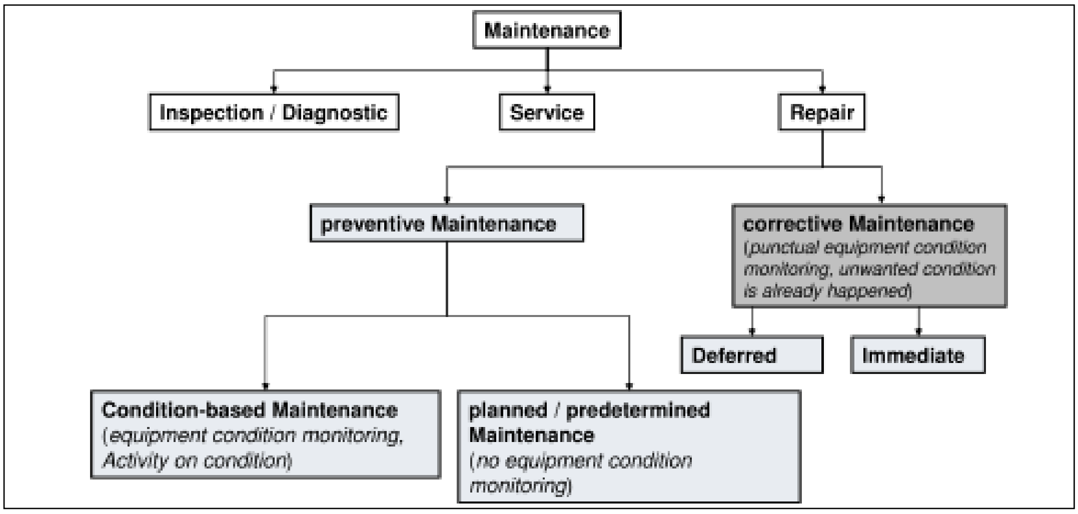


Figure 16: Classification of maintenance types according to EN 50126

Due to the complexity of a train its maintenance has to cover many involved systems and parts. Therefore regular inspections (preventive) and repairs (corrective) are involved. At the moment it is still common that maintenance is mainly preventive but future trends are more and more pushing towards a so called condition based maintenance regime to optimise resources by reducing preventive maintenance.[30]

Reliability centred maintenance (RCM) is another strong key word in this industry. The method is based on the assumption that every system will degrade and fail at a certain point. Common methods used are the Weibull distribution analysis and FMEA (failure mode and effects analysis).[31]

Reliability as performance metric is used for the evaluation of the maintenance effectiveness. It is a fact that every component has a maximum wear limit which is based on its design. No maintenance, regardless of how intense it is, can change that. Etwell states that the best strategy to ensure the highest reliability and lowest life cycle costs as simply doing “The Right Maintenance at the Right Time”.[32]

Train reliability in the UK is measured by “Technical Causalities” which looks at delays of 5 minutes or more. Values such as Mean Distance between Delaying Defect (MDBDD) or Mean Distance between Failure (MDBF) indicate how reliable a train is in operation.[33] Train manufacturer commonly use values like Failure in Time (FIT failures per 10^9 hours) or failures per million kilometres to indicate how reliable their systems will be.

Creating a maintenance plan requires a maintenance management system and defined maintenance intervals. The Railway Group Standard GM/RT 2004 demands the OEM to derive maintenance plans for new vehicles from risk assessments involving methods like FMECA[34]. In

[30] Siemens Life Cycle Engineering department, Bogie plant Graz, 04/2013
[31] Mobley (2002, pp. 6-10)
[32] Etwell (2001, p. 70)
[33] Morbey (2001, p. 140)
[34] Failure Mode, Effects and Criticality Analysis

the UK, the derived plan must be certified by the Vehicle Acceptance Body, which is part of the wider safety case held by the train operator.[35]

General requirements of what a maintenance plan should include are[36]:

- all maintenance activities
- the full schedule for maintenance actions including the periodicity for each item
- inspection programme
- definition of appropriate actions to ensure safe train operation
- technical instructions of activities

Maintenance periods and defined activities are derived and included in maintenance manuals before selling a product. The train maintainer can change these intervals by taking over responsibility considering the safety case of the train operator. With this in mind maintenance optimisation programs, which could include stretching maintenance periods, can be carried out on basis of experience gained (e.g. condition assessment) and the chosen maintenance strategy.

Maintenance optimisation is the process of reducing life cycle costs of a train by reducing the amount of maintenance work required while still assuring availability, reliability and safety. The operational aspects of fleet management and maintenance optimisation cannot be covered by the OEM because it is based on the actual product performance, which cannot be predicted with certainty. Maintenance optimisation in the operational environment includes more aspects like the amount of spare parts in stock, lead times for ordering replacement parts, synchronisation of maintenance issues, handling part failures and heavy repair, managing human resources and optimising the capacity of maintenance machinery involved.

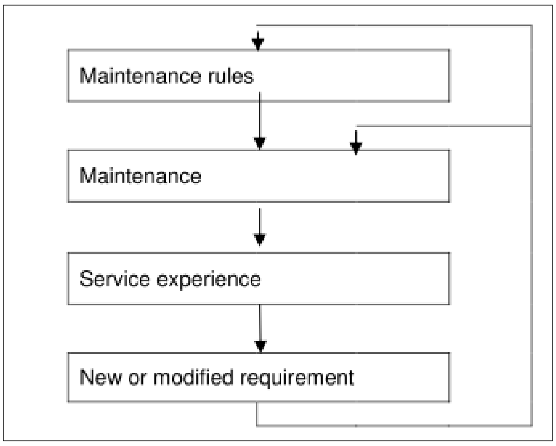


Figure 17: Iterative process of optimising maintenance according to EN 15313

This paper will only focus on the maintenance of wheelsets and gearboxes, which will be explained in more detail.

[35] Elliot (2001, pp. 117-122)
[36] Rail Safety and Standards Board (2012)

3.4 Wheelset maintenance

Wheelsets are the most safety critical assemblies on the train as the failure of its components will likely lead to the derailment of the train. Therefore the wheelset standard EN 15313 further defines performance criteria for maintenance.

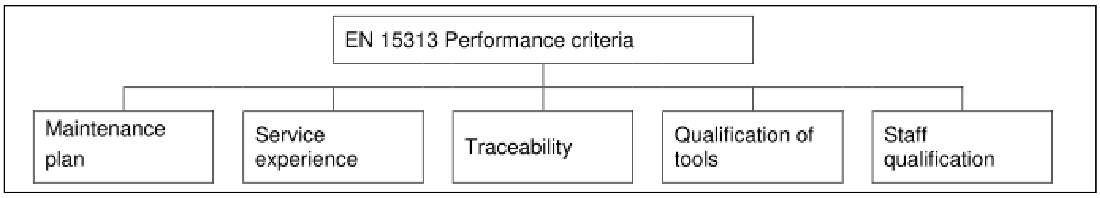


Figure 18: General maintenance organisation for wheelsets[37]

To ensure the safe functionality of the wheelset it is not only enough to comply with a maintenance plan and standards but also to ensure that staff and equipment is qualified for the purpose. Further ensuring traceability and service experience are part of ensuring a safe train operation. Required maintenance tasks and a representative wheelset maintenance plan will be shown on the following pages.

Maintenance of wheelsets can be divided in two main categories:

- Light maintenance, which includes inspections, measurements and checks on a regular and short term basis
- Heavy maintenance, which is referring to the overhaul of parts or assemblies

The Railway Group Standard GM/RT2004 defines maintenance requirements for wheelsets and its axle bearings by specifying following minimum requirements.[38]

Limits for the following points must be defined in a wheelset maintenance manual:

- Relative movement of wheels, axles, tyres and axle mounted equipment
- Cracks and fractures
- Dimension affecting running safety
  - Minimum wheel diameter
  - Tolerance between diameters of wheels on the same axle
  - Tolerance between diameters of wheels on the same bogie or rail vehicle
  - Minimum tread thickness
  - Back to back dimensions
- Flange and tread profile
- Wheel tread surface damage
- Wheel flat limits

The following points must be defined in an axle bearing maintenance manual:

- Maintenance plans shall include maintenance and overhaul instructions for bearings

[37] DIN EN 15313
[38] Rail Safety and Standards Board (2012, p. 9f)

- Requirements for
  - Floats, clearances
  - Grease, if applicable

Axle bearings are bought from suppliers and the responsibility for the maintenance manual is with them. Therefore maintenance optimisation programs and overhaul instructions have to be handled with the bearing supplier.

These limits are specified by Rail Group Standards but London Underground as a governmental body has the authority to adapt common standards for their purpose. Following, light and heavy maintenance of motor wheelsets will be discussed from an OEM's point of view and representative values given for intervals between the reoccurring maintenance tasks.

3.4.1 Light maintenance of motor wheelsets

Light maintenance includes visual inspection, measurements and an appropriate reaction on basis of specified wear or dimensional limits. Visual inspection means an accurate visual check of the wheelset for loose or missing parts and for damages from the middle or side canal (pit) in a maintenance facility.[39]

- Visual inspection of wheelset
- Inspection of profile dimensions
- Inspection of back to back dimensions
- Inspection of wheelset diameter difference
- Inspection of axial and radial run-out of both wheels
- Inspection of wheel for cracks
- Inspection of axle for cracks
- Visual inspection of axle box assembly
- Condition check of the wheelset bearing

These maintenance requirements shall be related to common intervals used in maintenance manuals:

[39] Siemens maintenance manual - Terms & Conditions

Maintenance task	Preventative Interval
Visual inspection of wheelset	2 months or 33k km
Inspection of profile dimensions	4 months or 50k km
Inspection of back to back dimensions	4 months or 50k km
Inspection of wheelset diameter difference	2 months or 33k km
Inspection of axial and radial run-out of both wheels	4 months or 50k km
Inspection of wheel for cracks	24 months or 300k km
Inspection of axle for cracks	24 months or 300k km
Visual inspection of axle box assembly	2 months or 33k km
Condition check of the wheelset bearing	48 months

Table 3: Light maintenance on wheelset and intervals[40]

Wheels wear in operation and the inspection of the wheel profile dimension includes measuring the flange height, flange thickness, flange angle dimension and so on. The measurement of the profile is either done with metal gauges or laser measurement equipment. Common wheel tread defects are flats, shelling, metal pick up, cavities etc. Considering the wheelset assembly the back to back dimension between the two wheels, the axial and radial run-out of the wheels and diameter differences have to be checked and must stay within defined limits. Light maintenance also involves the visual check for cracks and corrosion on wheels and axles. Further damage from stones, electric sparks or loosened parts are looked for and findings might require repairs.

[40] Are considered common industry standards, retrieved at Siemens Graz, 04/2013

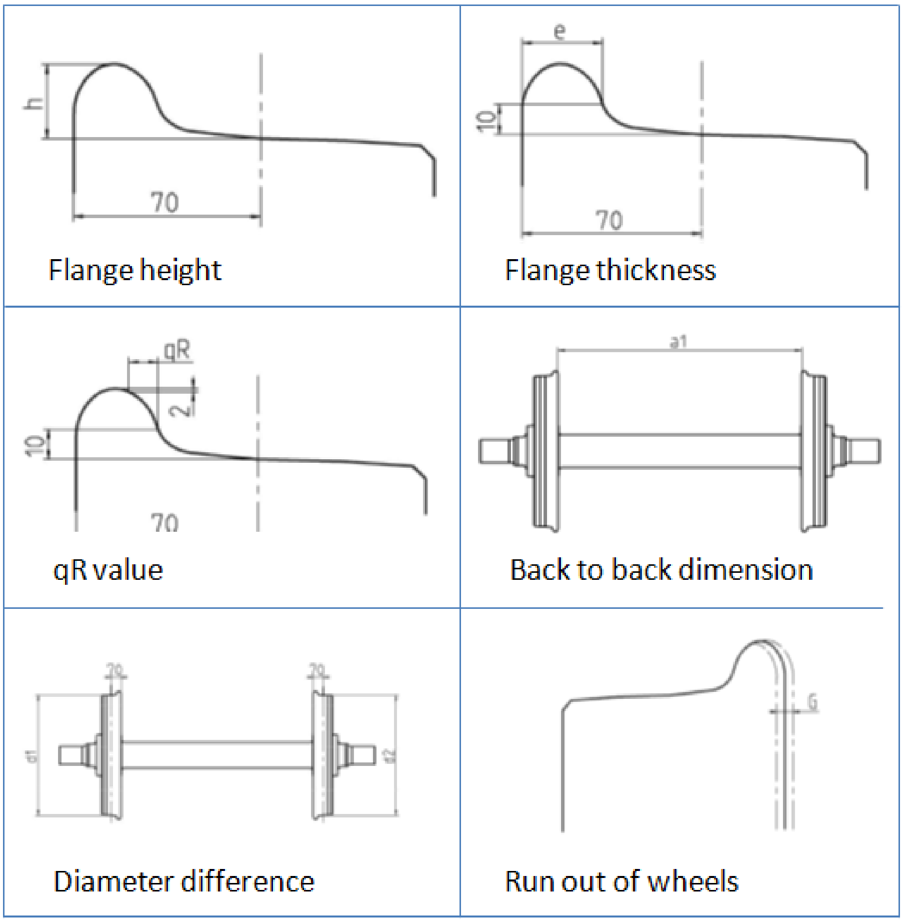


Figure 19: Wheel profile and wheelset measurements[41]

3.4.2 Heavy maintenance of motor wheelsets

Heavy maintenance is also referred to as overhaul. The definition of a bogie overhaul can be stated as: the removal, complete disassembly and reconditioning of the bogie in a repair workshop. For the subsequent assembly of the bogie only new parts and/or reconditioned, cleaned, undamaged and functionally faultless parts must be used.[42]

The overhaul process of a bogie:[43]

- Disassemble the bogie from the vehicle
- Clean the bogie
- Visually inspect the bogie
- Disassemble all components from the bogie according to maintenance manuals
- Perform all maintenance tasks according to the maintenance manual of the components
- Assemble all components to the bogie
- Assemble the bogie to the vehicle

[41] Referring to Siemens wheelset maintenance manuals
[42] Referring to Siemens bogie maintenance manual, Terms & Definitions
[43] Referring to the wheelset maintenance manual of metro “Inspiro Warszawa” motor wheelsets

- Adjust the bogie

The wheelset overhaul process includes delivering the wheelsets to an overhaul facility that has the required equipment which includes hydraulic presses for the axle bearings and wheel removals. Measuring equipment for NDT[44] testing is required and so are a back pressure test press, a paint shop and a gearbox testing rig. The overhaul process includes taking the wheels off first (if inboard axle bearings are in place) and then removing the axle bearings from the axle. After this is done the gearbox is freely accessible and can be demounted. Once all parts are removed from the axle it must be MPI[45] tested which ensures that no cracks have developed. The reassembling process includes putting on the overhauled gearbox and new or reconditioned axle bearings. New wheels can then either be put on by using heat treatment techniques or cold pressing. In the UK wheels are shrink-fitted and the exact positioning of the wheels is still done while they are hot and movable. Axle speed sensors are finally reassembled and the finished assembly can then be tested with an appropriate method like e.g. ultrasonic testing. In the end, the wheelset is tested for axial body run-out, tread run-out and wheel wobble which is shown in the figure below.

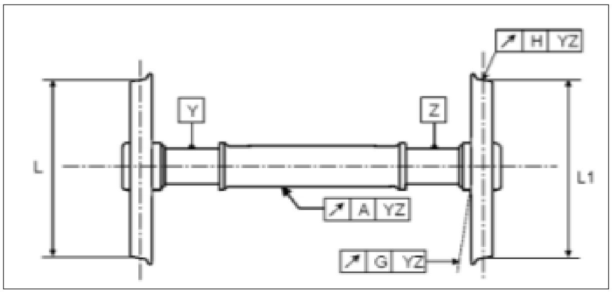


Figure 20: Datum for measuring the axle body run-out, tread run-out and wheel wobble[46]

3.5 Theoretical wheelset maintenance regime

A representative maintenance plan for wheelsets over a life span of 40 years is shown below.

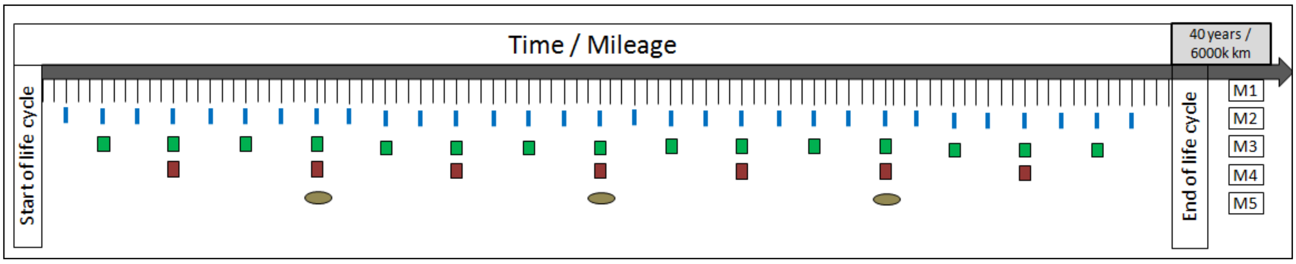


Figure 21: Theoretical maintenance plan and its intervals over 40 years

Maintenance activities (M1-M5) are shown on the time scale and are defined in the next table. The annual mileage travelled by the train is defined for this work with 150k km per year which sums up to 6.000.000km (six million km) over the 40 year life cycle. The intervals stated are preliminary estimations and will be analysed for the different design concepts in more detail.

44 Non destructive testing
45 Magnetic particle inspection
46 GM/RT2466, wheelset with inside journals

Level	Light maintenance	Interval	Occurrence in 40 years
M1	Visual inspection of wheelset	25k km / 2months	240x
M2	Wheelset measurement	50k km / 4months	120x
M3	Gearbox oil change	150k km / 1year	40x
M4	Ultrasonic testing	400k km / 32months	15x
	Heavy maintenance (Overhaul)	**Interval**	**Occurrence in 40 years**
M5	Wheel exchange	1500k km / 10years	3x
M5	Axle bearing exchange	1500k km / 10 years	3x
M5	Gearbox overhaul	1500k km / 10years	3x

Table 4: Preventative maintenance tasks and their intervals

3.5.1 Maintenance intervals

The length of maintenance intervals defines how often the work occurs in 40 years, which is important for costs. The overhaul intervals strongly depend on operational aspects and the condition of parts.

Long intervals between tasks results in less money spent over the life cycle but the risk of undetected failures increases. Visual inspections for example are not related to high material costs but they are done so often (240x) over the life cycle that the impact of personnel cost is significant. Defining these intervals is often difficult and requires predicting how components and systems will wear in operation. This means field data from possible customers is required, which highlights the importance of data acquisition before a bid appraisal. Commonly, intervals are defined on basis of experience gained (e.g. similar projects) and risk assessments. The same train in cold regions of Russia might have to have different maintenance intervals than one in Mediterranean Europe. Wear of parts, corrosion and material aging is influenced by a great number of parameters and difficult to predict over long periods (e.g.10years).

These intervals can be subject to a maintenance optimisation program once a train is in operation. Due to the early stage of the analysed bogie designs the OEM has to create maintenance manuals before the train is sold and therefore conduct risk assessments and use historical data to define these intervals. These intervals in combination with material and personnel cost will form the basis for the LCC models that will be explained in the next chapter.

3.6 Maintenance Costs

In the railway industry maintenance are a big share of overall train operating costs, thus are always considered in a bid appraisal before new rolling stock is purchased. In 1997, on behalf of London Underground, Holmes and Dymott published that maintenance costs for 560 trains (3880 cars) were around 60GBP million per year.[47] This financial impact shows the importance of this topic, especially as the number of tube trains in operation has increased. This chapter will cover the theoretical background of life cycle costing because maintenance costs are a part of it. LCC methods will be introduced and later implemented for cost models.

[47] Holmes and Dymott (1997, p. 57ff)

3.6.1 Introduction to Life Cycle Costing

Life cycle costing is widely used and the term well defined:

"*Life Cycle Costing is the process of economic analysis to assess the total cost of acquisition, ownership and disposal of a product*."[48]

"*Life Cycle Costing predicts and identifies all the costs associated with a product or system throughout its life, from product inception to its eventual withdrawal from service and disposal.*"[49]

Main uses of LCC[50]

- Long term costing/forecasting
  - (Affordability of a system)
- Bid appraisal
  - (As differentiator between offers)
- Trade-Off Analysis
  - (Could a more expensive part still be more cost effective over the life cycle?)
- Reporting
  - (As a management tool and monitoring metric)

The definition of the train's product life cycle according to EN 50126 should be considered before creating LCC models for a customer.

[48] IEC - International Electrotechnical Commision (2004)
[49] Mitchell (1998, p. 18)
[50] Mitchell (1998, p. 19f)

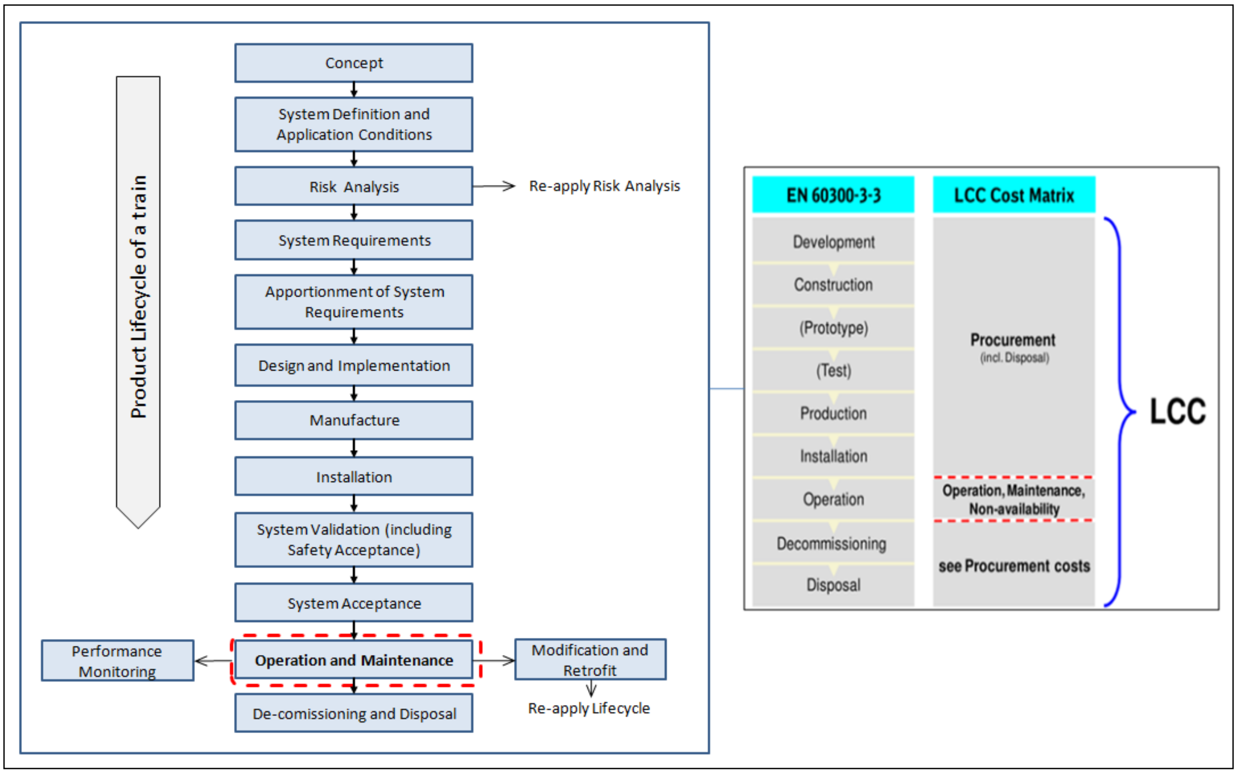


Figure 22: Product life cycle EN 50126 and life phases EN 60300-3-3 in cost matrix

A train's product life cycle begins with the early concept stages and ends with its disposal once it has been in operation for around 40 years. Due to this long time in operation, maintenance is one of the main contributors to the total life cycle costs.

EN 60300-3-3 relates all life cycle steps to a life cycle cost matrix, which defines how single modules fit into life cycle cost categories. It should be highlighted that costs occurring during the life cycle phases of "development" and "installation" are considered in the product price and are summarised as the procurement cost element. Also included in this element is the decommissioning and disposal of a train. Due to the great impact of train operation on costs, this life cycle phase is split up into the modules "operation", "maintenance" and "non-availability" costs. This thesis focuses on the "maintenance" cost group.

Maintenance cost structure

A 3-dimensional model will be used to explain how maintenance costs can be grouped. The following diagram shows this method for demonstrating the cost break down structure in the form of a cube. In this cube, cost elements accumulated are structured by a time-axis (when do costs occur); a cost-category-axis (e.g. material or personnel) and a technical-structure-axis (what part is considered).

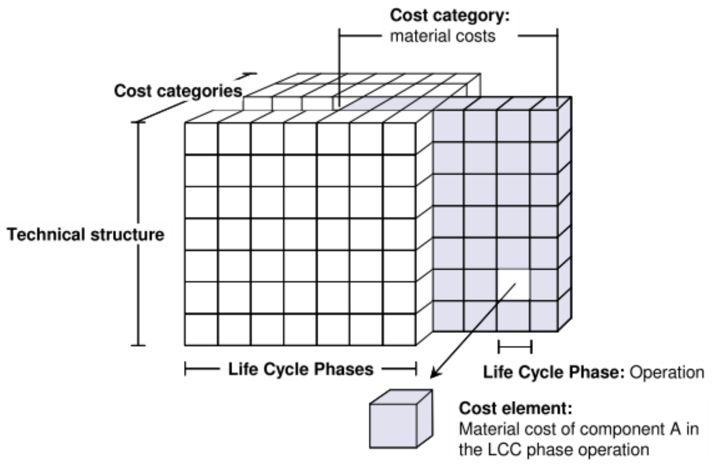


Figure 23: 3-dimensional LCC cost element concept[51]

The example of the maintenance task, “wheel measurement” shall help to explain how maintenance costs are structured and particular activities are allocated in the cube. In the technical structure of the model, wheel measurement could be found in the category “wheel”. The technical structure basically represents the bill of material of the analysed system (vertical axis). The wheel measurements are taken during the life cycle “operation” phase and repeated every 6 months for 40 years. This would be represented by small cubes on the horizontal axis. This measurement could take the average person 2 minutes, which multiplied with the hourly wage would result in personnel cost. This is represented by the allocation of the small cubes in the cost category of the above shown model.

The next chapter will describe what is involved in preparing a LCC statement for a bid and will describe the steps from the beginning to the end.

3.6.2 LCC process

The LCC process starts with the conceptual phase of creating the LCC model and ends after the life cycle of the product has ended.

During the conceptual phase, LCC tasks are specified and boundary conditions clarified. At this point it is stated which part or system is to be analysed and which key input values are used. Key values in the model could be the planned length of the train’s/component’s life cycle, the train’s annual mileage or hours particular components are in operation for.

The specified system/part to be analysed is then related to potential costs, which are broken down and categorised. (E.g. material costs, personnel cost etc.) In case of complex assemblies a technical breakdown and listing of its parts is required. This makes it easier to consider cost effects due to particular components and system functionalities. At this stage, variants and their specifications are defined and reproduced in parallel models.

The next step is bringing the models to life by including required data for all cost relevant parameters. Data has to be gathered, analysed, assessed and uncertainty factors kept in mind.

---

[51] Innotrack (2006, p. 21)

The implemented LCC model is then run, which is commonly done with a computer supported tool like MS Excel. Costs can be calculated either using a dynamic or a static method. The net present value (NPV) for each variant is a potential result and could be benchmarked and used for choosing one of the variants.

After the variant decision, the bid appraisal can be started but the customer needs to agree to the assumptions made and methods used in the model. The type of contract to be awarded defines the LCC business case for the rolling stock manufacturer. Typical business cases are: LCC with or without guarantee; LCC including a maintenance contract for the product; LCC with spare parts supply. Maintenance costs for a train are often stated as €/km.

After the product is sold and the system is in operation, actual performance indicators can be monitored and compared with values that were forecasted. If the customer has no monitoring in place it is unlikely that claims towards the OEM are successful. Especially the predicted life cycles of parts could be shorter than promised, which increases the customer's cost of operation.

But feedback from operation is crucial for the OEM as well because lessons learned provide the opportunity to improve the product and to improve the LCC models. As there will be uncertainty with most of the LCC models the feedback is crucial and helps to gain more experience and data for the next offer.

Ultimately, the customer should be involved in nearly every process stage, starting with providing required information and ending with a control and feedback loop.

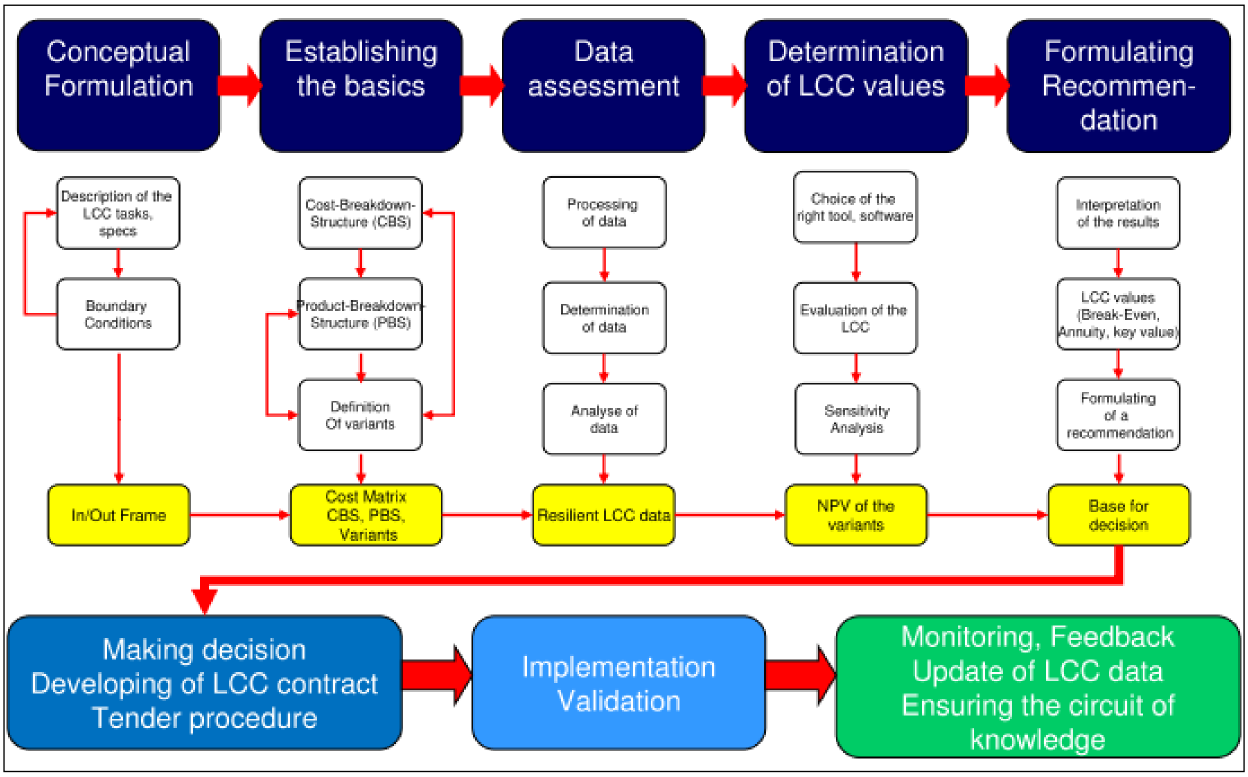


Figure 24: LCC process in railway engineering and main steps to be followed[52]

[52] Innotrack (2006, p. 17)

3.6.3 LCC methods for maintenance

In this section, life cycle costing methods are investigated and their suitability for decision making compared. Static calculation methods will be compared with dynamic ones.

Static LCC calculation is a method in the area of investing and costing in which the investment of different variants is stated and compared with the capital outflow and cash inflow over the life of the product. A standard investment is only justified if the return on the investment pays the initial cost, which is referred to as payback time. Time value of money is not included and the costs and profits of variants are simply compared.[53]

Applying this method to comparing maintenance costs can simply mean adding all occurring costs over the life span. The total sum of cost can be used to compare different variants and represents a part of their cost of ownership. Neglecting cash inflows for analysing wheelset maintenance costs is allowable as different designs do not influence the money earned from train tickets sold. The dynamic method builds on these principles but additionally includes the time value of money.

Dynamic LCC calculation is also referred to as discount method and includes the time value of money. The time value of money is the potential of capital to earn an interest on the free market (e.g. in a bank account). A positive interest rate therefore suggests spending money as late as possible because interest is gained over time. The return on an investment should by definition not be less than the market rate of interest.[54]

A simple example shall be given: Spending 1.000€ one year later, assuming an interest rate of 5% on capital, would result in a net present value of 952.38 EUR. This shows that 1.000€ would earn 47.6 € in interest in a year and the expenditure shifted back for this period would appear as less costly. This means maintenance issues later in the life cycle are not as cost influencing as the early ones. The calculation of the net present value for maintenance costs can be written as:

$$\text{NPV over 40 years} = \sum_{k=0}^{n} \text{Cost}_k * \text{Discoutn Rate}_{\text{year k}}$$

Formula 1: Calculation of Net Present Value (NPV) over n=40 years[55]

The formula includes the main NPV components:

- Cost estimation
- Discount rate
- Period of analysis

Cost Estimation: Cost estimations over a period of 40 years are critical and the prediction is difficult. This is explained later on as uncertainty and is related to risk management.

---

[53] Dale (1993, p. 3)
[54] Flanagan, Norman, Meadows, and Robinson (1989, pp. 17-58)
[55] Dale (1993, pp. 6-10)

Discount Rate: The discount rate defines the time value of money and therefore the excess or shortfall of costs. A positive net interest rate on money means that yearly expenditure is multiplied with a factor smaller than 1. Over the years, this factor declines and the discount rate specifies how fast it is declining. Therefore it has a dominant influence and can be more important for the sum than the yearly costs themselves.

$$\text{Discount Rate} = 1/(1+r)^t$$

Formula 2: Discount rate with interest (r) and over a time period of (t)

The discount rate could mean that an overall less costly product (static calculation) could lose against the other one that allows a later expenditure of money. As long as the net interest rate (r) gained on capital is positive, a delayed expenditure is preferable. The exponential nature of the discount rate is defined as the inverse of the compound net interest curve, which is shown in the diagram below.

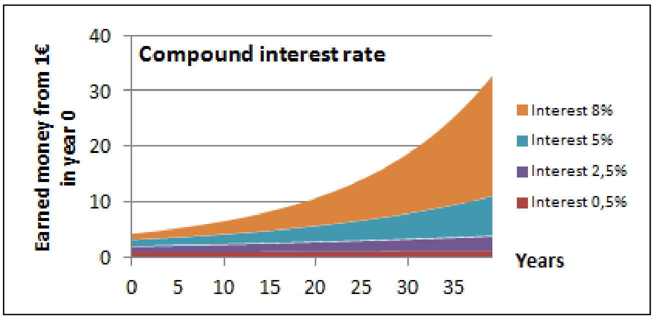


Figure 25: Influence of interest (r) on the time value of money

Period of analysis: If the life cycle is initially not defined it presents another varying parameter and models become more complex and make a concept decision more difficult. A defined life cycle of 40 years is used for all variants that will be compared.

Both, the static and dynamic approach are easy to understand from a theoretical point of view. But there is a hidden complexity involved in predicting costs for a system like a bogie or wheelset. The difficulty is identifying what maintenance activity causes what cost and how reliable a system will be. During the life cycle of a train, prices and wages will develop and predicting the future is always uncertain.

3.6.4 Uncertainty and risk

When considering a life cycle of 40 years, variables involved in LCC models are considerable and uncertainty of data will be the main problem faced. Common questions to ask are: Which material prices will be at hand in x years, how will hourly wages develop and what actual performance will the fleet have in operation compared to assumptions made in the conceptual phase?

The white paper[56] summarises three main reasons related to uncertainty in LCC models:

- Parameter values are not well known because of lack of data
- New developed systems cannot really be related to historical data
- Failure rates and life time of components are described by probability density functions rather than with exact values

Uncertainty can often be handled with risk management. What risk management cannot do is remove the need for decisions and judgements of the LCC analyst. Inevitably this results in a degree of subjectivity. Risk management only identifies the areas where judgements are required and therefore gives a hint where more effort for research is needed.[57]

Handling risk effectively requires identifying the biggest risk factors. This could be done with conducting sensitivity analyses and with considering probability distributions of events. Theoretically, every input parameter in an LCC model should be modelled with a probability value but this level of detail becomes too complex for most applications. Limiting the probability functions to component parameters like failure, wear-out and repair may be beneficial. Probability distributions can be handled with methods like the “Weibull analysis” and more complex simulation methods like the “Monte Carlo simulation”.[58]

3.6.5 LCC as benchmark method of variants

H.K. Jun and J.H. Kim conclude in their paper that life cycle costing is the most cost effective approach for choosing between a series of alternatives because the total cost of ownership is included.[59]

Most of the time only the costs for the initial procurement are known exactly while all other cost elements have to be forecasted and are subject to uncertainty and assumptions. Even though there are quite reliable clues about these costs, it still may be that different system variants inherit different types of costs. This fact is included in a direct LCC comparison. LCC can therefore be used as decision criteria for purchasing which makes it very important for tenders.[60]

LCC statements for bids are common in the railway industry, which means they are important for choosing the product variant to offer. A benchmark of variants can be made either with or without a discount rate and again with or without inflation included. The discount rate applied can change the ranking of variants in certain cases as a difference in time where money is spent can be included. Therefore, the method used for bid appraisals has to be defined by the costumer.[61]

How accurate LCC models are, depends on the data available. The advantage of using LCC models for a variant comparison is that a few uncertainty values, which equally apply to all

[56] Innotrack (2006, p. 35f)
[57] Flanagan et al. (1989, p. 85)
[58] Gibbs (1998, pp. 31-44)
[59] Jun and Kim (2007, pp. 1989-1994)
[60] Martinsen, Rahn, Hermann, and Hochbruck (1997)
[61] Siemens sales department London, 07/2013

concepts, do not contribute to a difference. This means that as long as LCC models are used for a concept decision they are suitable for the purpose. As soon as sums from LCC models are used for warranty or cost per kilometre statements it becomes critical and a company should include a margin for economic risks.[62]

3.6.6 LCC models for train maintenance

Two different types of cost models can be distinguished by their point of view and intention.

1. LCC models developed by the OEM before selling a product
2. LCC models implemented in the environment of train maintenance

Adding to 1; the OEM demonstrates the maintainability of the product, states life cycles and reliability values, which might be related to warranty agreements. Costs are theoretical and do not include all overhead costs or operational issues. The required data is simply not available for the manufacturer of the product. Nevertheless, a part of these overlaying costs might be included in the hourly wage used for calculating personnel costs.

Adding to 2; train operators use LCC models to monitor the costs created, which is occasionally part of the maintenance management system. Models include spare parts, availability, actual train reliability, personal planning, equipment utilisation etc. The difficulty faced is to compare both models. This can only be achieved by defining key criteria between customer and producer.

3.6.7 Siemens cost models[63]

This thesis will further implement maintenance costs in established cost models used within Siemens. The key aspects for these models that need to be answered are:

- what task and how often is it executed in the life cycle (maintenance plan, intervals)
- how costly are parts to be replaced (material costs)
- what is involved in maintenance processes and man hours required (personnel costs)
- how reliable are components (what failure rate is stated)
- is the synchronicity of maintenance tasks ensured (reducing train down time)

and includes the following main types of maintenance that create costs:

- Light Maintenance
- Heavy Maintenance
- Corrective maintenance

The two main cost types are:

- Material costs
- Personnel costs

[62] Siemens warranty department Graz, 05/2013
[63] Referring to Siemens methods and models

The manufacturer can influence these costs by choosing the components installed and by ensuring that the maintainability of the system is optimised. Influencing factors are the required processes, accessibility of components and the maintenance equipment needed.

Siemens' whole life costing (WLC) model is an attempt to go a step further and includes not only the life cycle costs of a train but also costs of other influenced systems. Examples include track wear, tunnel cooling, management of stations and so on. Especially for a comparison of entire train variants this ends up being a very complex system just considering the logic correlation, influence and weight of involved parameters.

An example can be given to describe the difficulty by just thinking about one train component. Would it pay off in terms of whole life costs to use a more expensive component in order to change the train drive dynamics? Does it pay off if it is less track damaging and is it related to a different amount of energy consumption? Increased energy consumption would influence tunnel cooling and also might require different maintenance regimes and processes. If the system is new there might be a higher probability of failure. Some of these questions can only be answered if enough customer specific data is available and by dedicating a considerable amount of time and research to it.

Nevertheless, bid appraisals require LCC statements for the whole train and a bogie is one of the main sub components. The current WLC approach implements LCC models of sub assemblies like the wheelset in the overall model. Therefore it is important to consider overlaying effects that might be more decisive than the maintenance costs of a single part. Sub component models are calculated with a static LCC method and then fed into the overall model. In this overall model, discount rates are applied in order to consider the customer's time value of money. This discount factor can be positive (when capital interest is bigger than inflation) or negative (when capital interest is lower than inflation).

The model used for the following comparison of wheelset variants is an Excel based tool that is built up as follows.

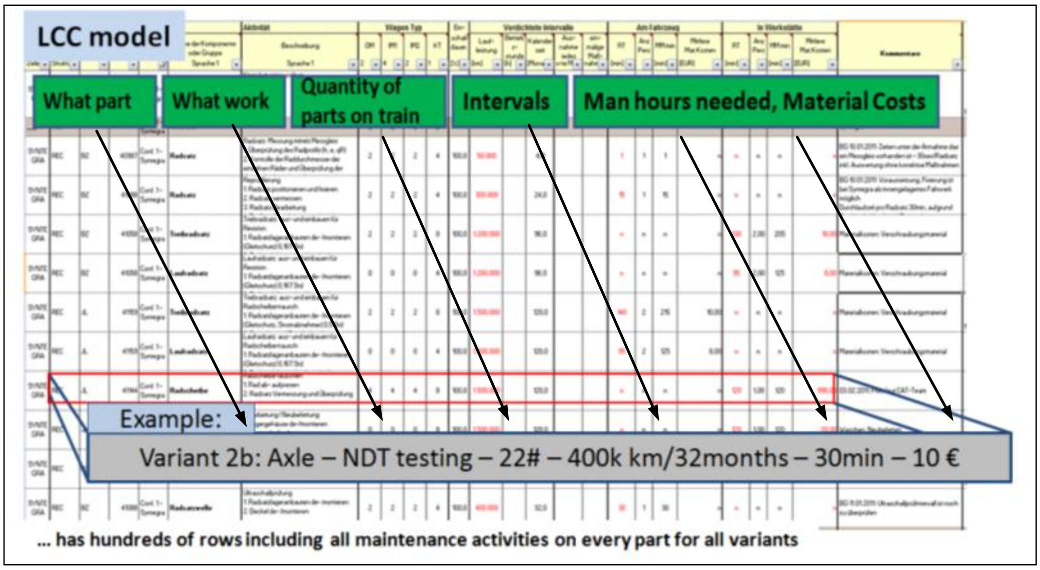


Figure 26: Siemens LCC tool and example of implementing a maintenance activity[64]

This MAST tool (Maintenance, Analysis, Spares, Tools) includes every part of the bogie in a tabularised file and costs are calculated with a VBA (Visual Basic for Applications) supported process in the background.

Extending this tool with a dynamic costing method is promising as it includes the time value of money and the business Transport for London case development manual requires products to be analysed this way.[65]

3.7 Summary

This chapter gave a short overview about the definition and history of maintenance from a general point of view and has related various maintenance types to the railway industry. Preventive Maintenance (PM), Corrective Maintenance (CM), Improvement Maintenance (IM) and Predictive Maintenance (PDM) were introduced. Metrics of how maintenance can be measured were explained and maintenance plans and their optimisation potential discussed. Comparing the OEM's point of view with the train maintainer's perspective showed the differences faced. The development process of maintenance plans was further explained and related to the safety case of train operation.

For the more specific analysis later on it was necessary to explain maintenance requirements on wheelsets and a list of maintenance tasks were categorised in "light" and "heavy" maintenance. Finally a theoretical maintenance program over 40 years has been created and maintenance intervals discussed.

64 Siemens LCC tool, Graz 04/2013
65 Transport for London (2009)

Life cycle costing has turned out to be appropriate for calculating maintenance costs and static and dynamic methods were compared. The Siemens LCC models were introduced and the difficulty due to uncertainty discussed. Nevertheless, costing models for maintenance require many input parameters and detailed information about cost factors of the product's operational environment. The bogie designs and their wheelsets at hand are still in a conceptual stage and provide only a small amount of solid data. The main focus of the cost modelling will therefore be the preventative maintenance plan.

LCC proposals are often related to warranty agreements and the OEM might have to guarantee certain product performance metrics. These guarantees can be problematic if not enough field data is available, which is necessary to reduce the economic risk involved. This work will further aim to gain as much field data as possible in order to make the cost modelling more reliable. Once a train or fleet is in operation, more data is available and the costs initially predicted can be compared. For the particular analysis this won't be possible for the next ten years.

The proposed Siemens bogie design concepts will be explained in the next chapter and LCC models set up for each variant. A final recommendation of the most cost effective variant will be made by applying the introduced LCC methods and models.

4 London Underground specifics

Previous chapters have covered the topics “railway environment”, “maintenance” and “life cycle costing”. This theoretical background will be applied to analyse and calculate maintenance costs of the four Siemens wheelset design concepts with implementing field data from the London Underground. The Siemens feasibility study will be introduced and the LU maintenance strategy explained.

4.1 Siemens feasibility study

The Siemens feasibility study, which developed new and innovative metro concepts, was conducted during the last two years. A top down approach was chosen to explain the new system and its interfaces, starting with the train concept and continuing with the bogie designs and their wheelset assemblies. Eventually, the main cost drivers will be identified and research questions for the further work derived.

The Siemens Vienna plant has developed several train concepts suitable for the London Underground. The 9 car unit vehicle shown below will be analysed in context with its wheelsets installed.

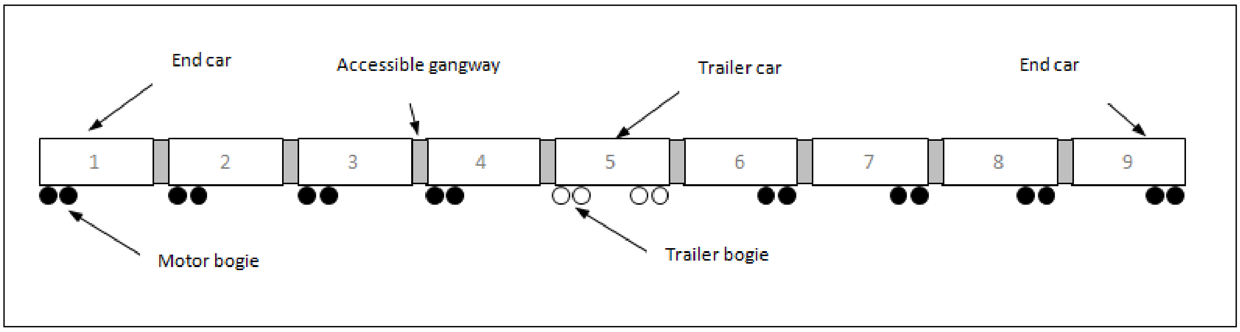


Figure 27: 9 car train vehicle concept[66]

Train configuration[67]: Bo’-Bo’-Bo’-Bo’-2’2’-Bo’-Bo’-Bo’-Bo’

B... two driven wheelsets
2... two non driven wheelsets
O... single driven wheelset
‘...mounted in a frame (not mounted on train carriage)

The 9 cars are connected with couplers and accessible gangways. Each motor car is comprised of a carriage and one bogie, which it is mounted on. Only the trailer car in the middle includes two trailer bogies without a drive train installed. The whole vehicle therefore only has 10 bogies and is a design proposal with a reduced number of bogies so that maintenance efforts and thus costs are reduced.

[66] Referring to Siemens feasibility study
[67] Haigermoser (2002)

As many of the considered cost calculations are based on the entire train, the number of particular wheelset components is shown in relation to it: 40 wheels, 20 axles, 40 axle bearings, 16 motors, 16 gearboxes if existent, and 40 axle boxes.

Train configurations have an important impact on maintenance plans and further on wear of parts in the bogie. Bogie design concepts are now discussed in more detail.

4.1.1 Bogie concepts and the drive assembly

In order to understand the differences between the bogie concepts, each of them will be explained briefly. The drive train assembly is one of the main differentiators between the four designs and thus influences related life cycle costs due to differing maintenance requirements.

"Inspiro" – the bogie platform

Designs were derived from the Siemens "Inspiro" platform which is the platform for metros. The concepts are also very similar to the Siemens SF7000 bogies, which are built in to the "Thameslink" trains. All these designs share the common feature of axle bearings being mounted behind the wheels and thus allowing the frame design to be smaller and lighter. If wheels have to be changed, bearings are not affected as they do not need to be removed first.

All bogies that will be compared share the following common attributes: Articulated bogie frame, inboard axle bearings, two air springs, installed torsion bar and two tread brake units per wheelset axle. Optionally, the wheelset guidance can be realised as dog bone bushing or for more elasticity, by using hydro bushes.

Direct drive design (further referred to as Var. 1)

Within Siemens this concept is known as “Syntegra”, which is an innovative design tested on the underground in Munich. An AC engine is used as gearless direct drive, which is fully mounted on the wheelset axle. The rotor of the motor is integrated into the wheelset axle. This has to be considered for wheelset and motor overhauls. Furthermore, the wheelset axle bearings are simultaneously used as motor bearings, which is a further reduction of parts. A disadvantage is the increased unsprung mass which is considered a factor for track wear.

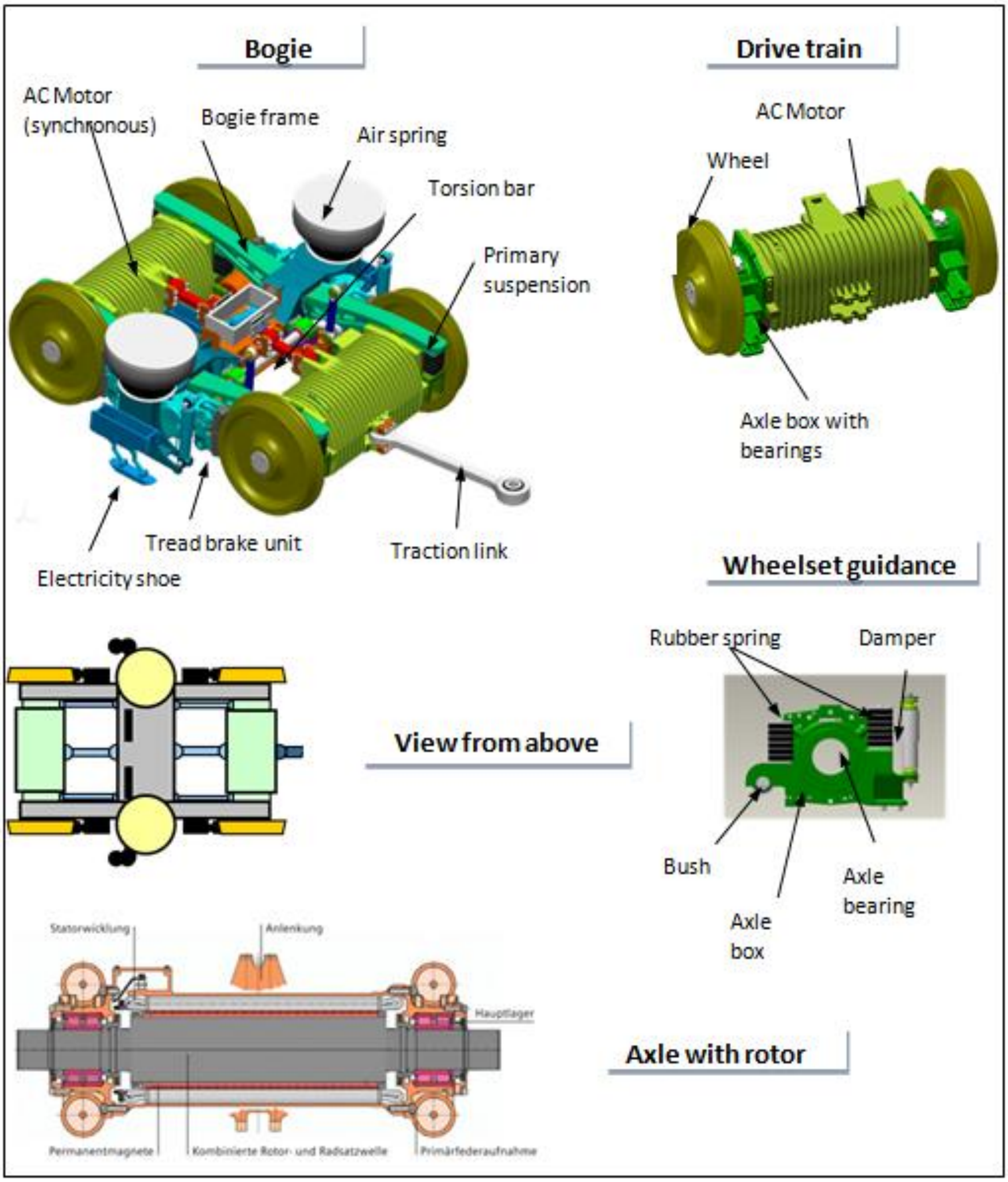


Figure 28: Bogie Design Concept Var. 1 (Syntegra)[68]

[68] Concept Var1 in Siemens feasibility study, 2013

Nose suspended gear drive design (further referred to as Var. 2a1)

In this concept the engine is mounted to the bogie frame on one side and carried by the axle on the other side. This means the weight of the motor is distributed between axle and bogie frame. It is a common way of building bogies and also can be found in locomotives. A single stage reduction gearbox is used due to the small distance from axle to engine. The engine is mounted on the axle via a suspension tube and two bearings so that a relative movement between engine and gearbox is prevented. The motor output shaft is used as the pinion for the gearbox and therefore no additional motor coupling is needed.

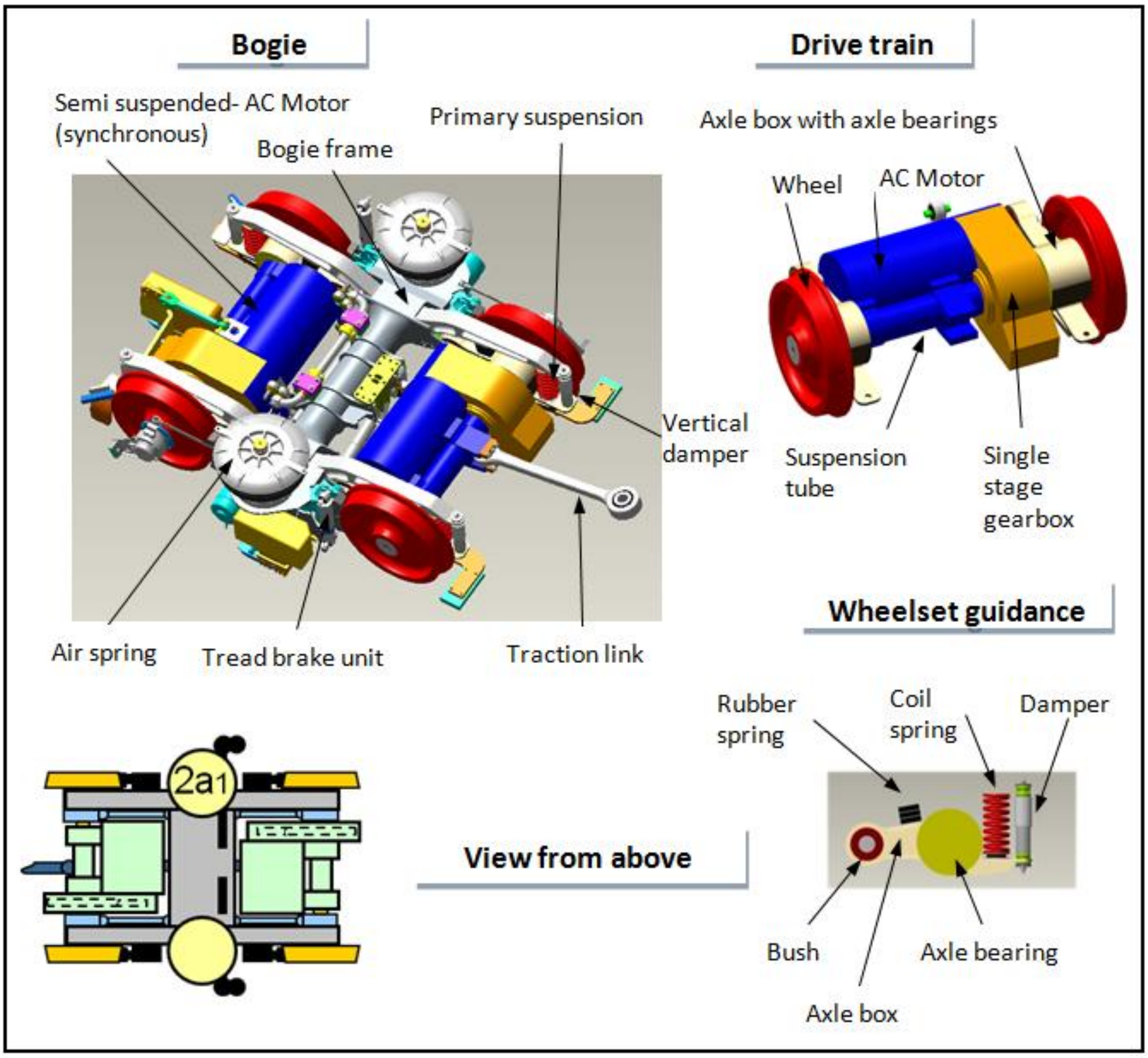


Figure 29: Bogie Design Concept Var. 2a1, Semi suspended design[69]

[69] Concept Var2a1 in Siemens feasibility study, 2013

Semi suspended gear drive design (further referred to as Var. 2b and Var. 3a1)

In this system the AC motor is fully mounted on the bogie frame and thus its mass is damped by the primary suspension. A curved teeth coupling is installed between the motor and the two stage reduction gearbox for transferring torque to the axle. The concept is designed in a way that either a synchronous (Var2b) or an asynchronous engine (Var3a1) can be installed.

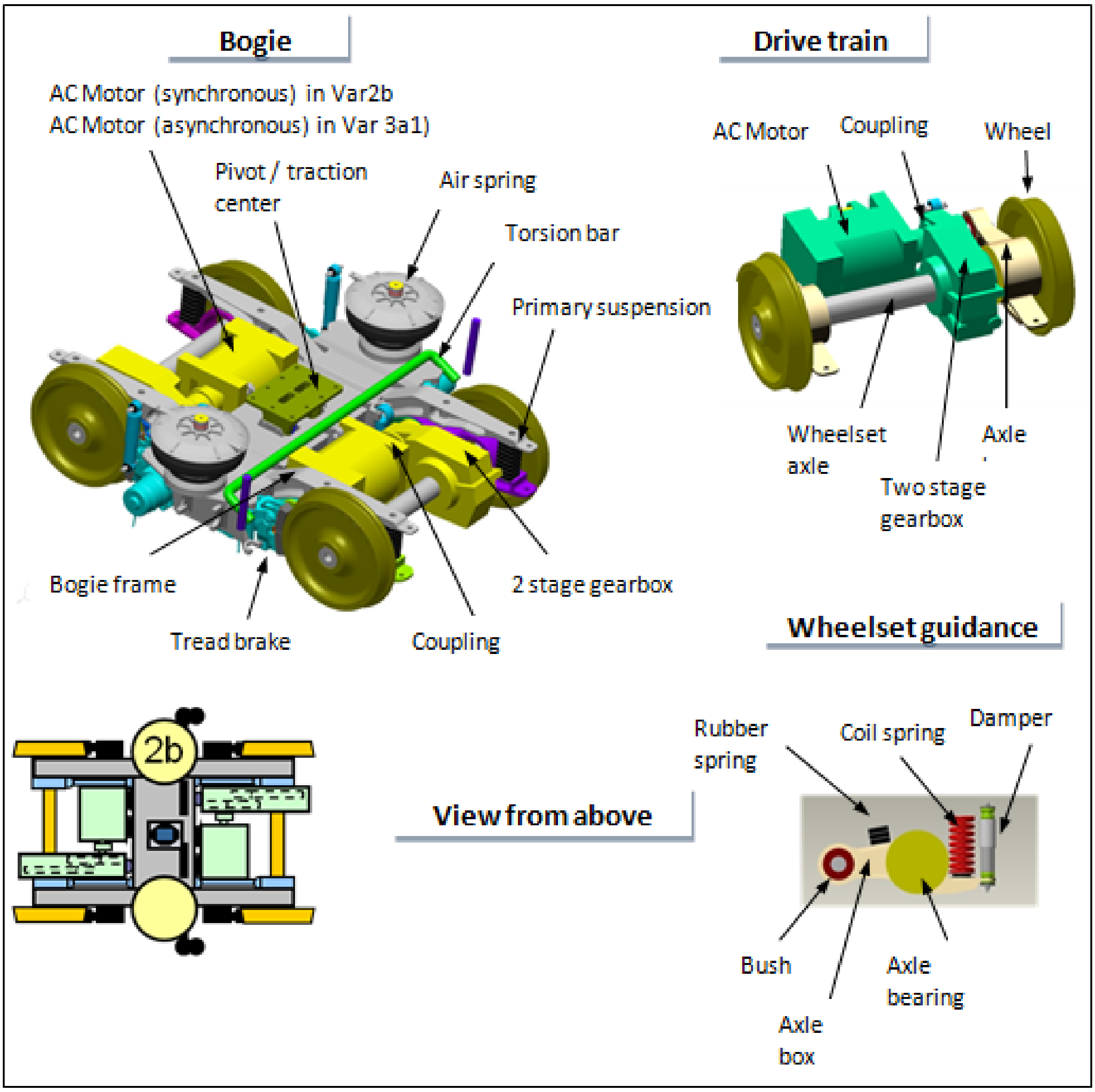


Figure 30: Bogie Design Concept Var. 2b & Var. 3a1[70]

Wheelset and gearbox

The wheelbase distance, unsprung mass and the weight of the whole bogie characterise some of the most important differences associated with bogies.

[70] Concept Var2b and Var3a1 in Siemens feasibility study, 2013

	Var. 1	Var. 2a1	Var. 2b & Var. 3a1
Wheel diameter [mm]	700 - 650	700 – 650	700 – 650
Wheelbase [mm]	1.600	1.600	1.800
Unsprung mass per axle [kg]	~ 2x Var2b	~ 1.5x Var2b	~ 1.000
Weight of whole bogie [1000 kg]	5.300	5.000	5.000
Connection to car body	Traction link	Traction link	Traction centre

Table 5: Technical key data of wheelsets compared

Wheel: The wheels are, for metros, comparatively small, with a chosen initial diameter of 700 mm. In operation, wheels wear and metal has to be turned off at particular intervals or on condition in order to restore the profile. The scrap size diameter is 650mm, which provides a tread thickness of 50mm on the diameter that can be used for turnings on the lathe.

Axles: Due to weight reduction and easy access during ultrasonic testing, all axles are designed to be hollow. Due to the installation of inboard bearings the axle diameter at this area is bigger than it would be for outboard bearings. Stiffness and deflection of the axle have to be considered to prevent fretting, which is corrosion that is caused by micro movements.

Axle Bearing: With all concepts, inboard bearings are installed, which means they can be found behind the wheels, on the axle. Common bearings are either taper roller bearings or cylindrical roller bearings. Both are an option in this project phase.

Gearbox: Variant 1 does not have a gearbox; Variant 2a1 has a one stage gearbox with a suspension tube installation and Variants 2b and 3a1 have a two stage gearbox. Both of them are reduction gearboxes and allow the motor to rotate faster than the wheelset. In the direct drive Var.1, the motor has to rotate at the speed of the wheelset.

Motor: Alternating current (AC) motors are used in all concepts and are connected to power converters. With concept Var.1, the direct drive, it is important to consider the combination of unsprung mass on the axel and the axle bending, especially because the gap between rotor and housing should be as small as possible. Additionally, the motor has to spin with the same speed as the wheelset axel. This means the direct drive motor has to provide the required torque at low rotational speed. Concept 3a1 uses a grouped motor control with one power converter in place for two motors. All other concepts provide a power converter for every motor and thus wheel diameters do not need to be matched within a small tolerance. This fact will be taken into account when considering the wheel life cycles of Var. 2b and Var. 3a1, which are identical in every other respect.

	Var.1	Var. 2a1	Var. 2b	Var. 3a1
Axle	Hollow	Hollow	Hollow	Hollow
Axle Bearings	Part of motor	Inboard: either taper roller or cylinder roller bearings	Inboard: either taper roller or cylinder roller bearings	Inboard: either taper roller or cylinder roller bearings
Gearbox	no	Single stage with suspension tube bearings	Two stage with motor coupling	Two stage with motor coupling
Motor coupling	no	no	Curved teeth coupling	Curved teeth coupling
Motor	AC - synchronous	AC - synchronous	AC - synchronous	AC – asynchronous
Motor control	Independent motor control	Independent motor control	Independent motor control	2 motors controlled with one power converter

Table 6: Overview of design variants

Due to the different components of variants their biggest maintenance costs might be different, which will be analysed in the next chapter.

4.1.2 The biggest cost factors

Wheelset LCC models have been created for each wheelset concept described above and a first sensitivity analysis of wheelsets with their gearboxes brought up the largest cost factors. The analysis is based on material and personnel costs accumulated over 40 years. The distribution of costs per wheelset and gearbox is shown in relation to their total maintenance cost.

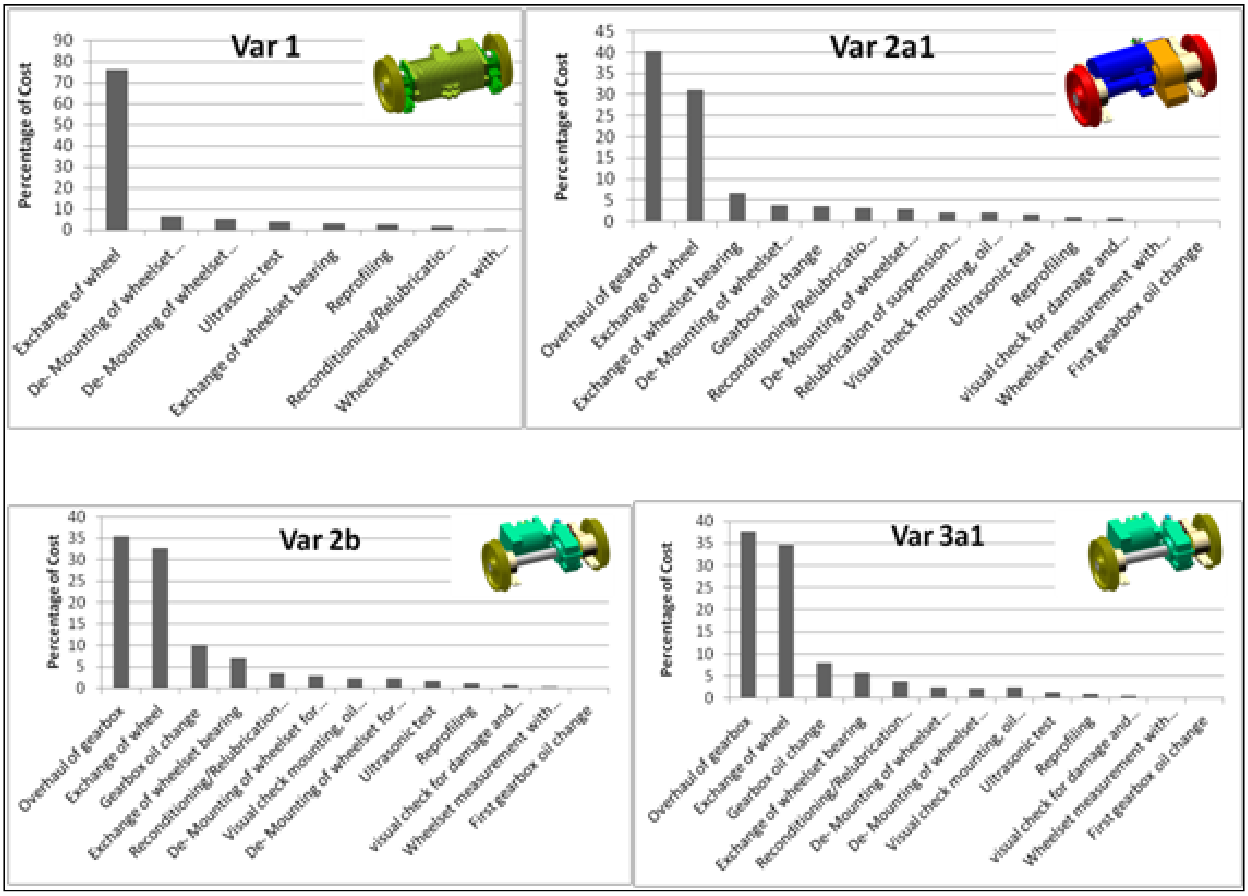


Figure 31: Maintenance cost contributors of wheelsets including the gearbox and their magnitude over 40 years

The exchange of wheels and the overhaul of the gearbox are by far the most dominant costs.

In Var.1 it can be seen that the costs for wheel renewals are above 70% of total maintenance costs. With the three other concepts this cost type’s contribution is in a range of 30% to 35% as their design includes a gearbox, which is their most dominant cost factor.

Var1: Due to the fact that no gearbox is installed, the wheel exchange costs become the biggest concern. The many maintenance activities required for the gearbox are obsolete, which results in the lowest amount of total costs over the life cycle of the wheelset.

Var2a1: Here, the overhaul of the gearbox is the most expensive maintenance activity especially because the design of the gearbox requires the consideration of the suspension tube mounting and its additional bearings.

Var2a1 / Var3a1: Have the same design and require the same maintenance processes. The only difference is created by the current converters of the bogie. It is assumed that this implies a shorter wheel life cycle with Var3a1. (This assumption is not analysed further in this thesis) The shorter wheel life cycle would cause one more wheelset and gearbox overhaul during the 40 years life cycle as it has to be carried out every 8 years. The suggested wheel life cycle of 10 years, instead would only require three overhauls in 40 years (Var2a1).

The next figure directly compares predicted costs (€) of particular designs.

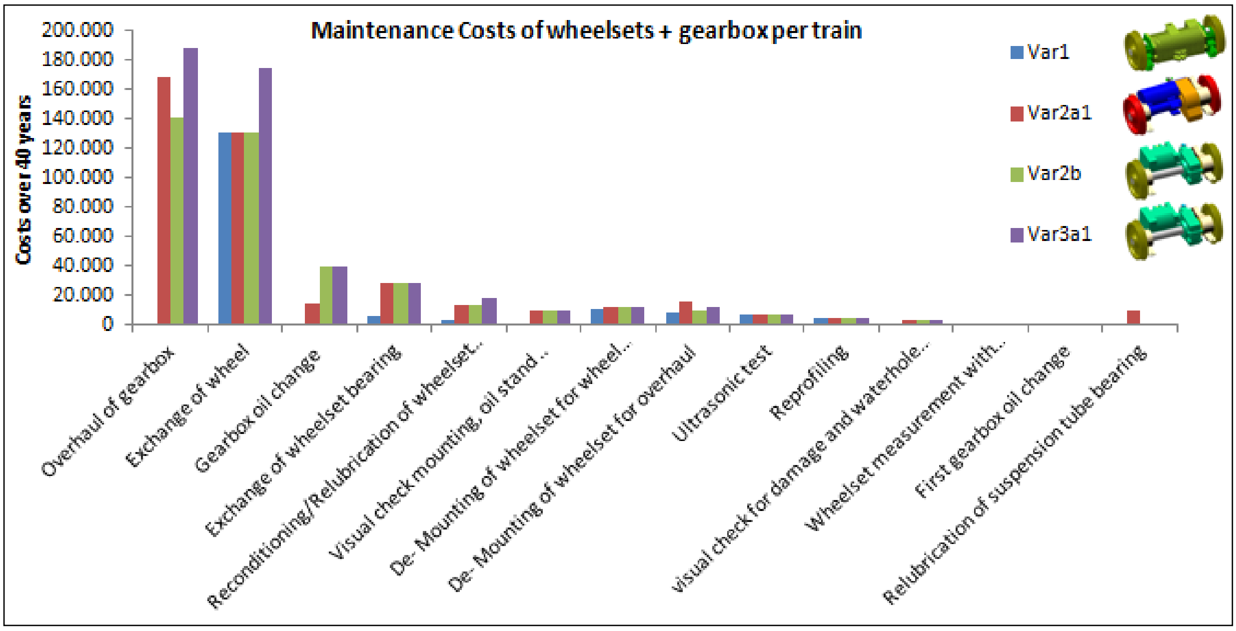


Figure 32: Direct comparison of maintenance cost factors

Figure 32 shows where cost differences occur and directly compares the variant difference in the particular cost categories. The total sum of maintenance costs for each concept and 40 years is shown in Figure 33.

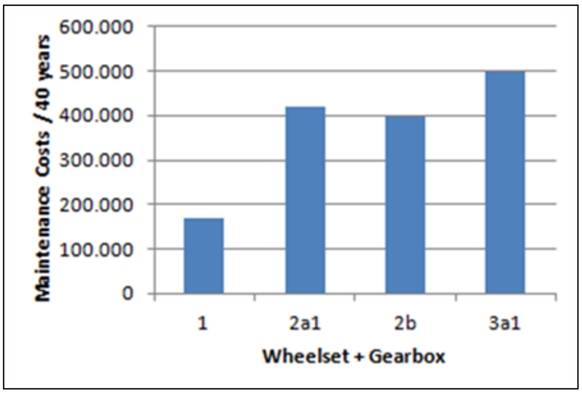


Figure 33: The accumulated maintenance costs of wheelset plus gearbox over 40 years and per 9 car train (own illustration)

These costs are the result of preventive maintenance activities defined in the maintenance plan. But due to the early concept stage these costs are predictions and will be improved subsequently. A list of relevant questions was derived and is the basis for field data gathering.

4.1.3 Research questions for LCC models

The data entered in this cost model is uncertain and especially wear predictions and the operational environment was initially not known. This is due to the early project phase, a lack of knowledge about maintenance facilities and equipment available and the maintenance strategy of the potential customer London Underground. It was considered useful to include an assessment of how reliable existing LCC data is. Further chapters will be part of improving this data reliability.

	Confidence Level
1	unknown vlaue
2	there is a rough idea about the range of the value
3	subjective judegement of a person who workes in the particular field
4	expert opinion, reference to other projects, at least two sources
5	certain value, references can be made

Figure 34: Confidence level rating for data reliability

The next figures show which data related to the wheelset and gearbox maintenance was considered as uncertain and how the planned approach looked like.

Category wheelset	Nr.	Assumptions	C.L.	Description of assumptions	Prio	Derived questions	Planned approach
Measurement of wheelset	1	Interval 50k km	3	A usual value for Underground applications	++	What interval is used at LU	Interview with LU employess and depot visits
	2	Measurement-rail is available	2	State of the art but not known if installed	+	Does LU have this device, how do they measure?	Visiting LU depots and REW
	3	30 sec. per wheelset	2	With assumption that measurement rail is available	+	In what depots is a measurement rail installed?	Interview with LU and with Siemens consultant
Reprofiling strategy	4	**Interval 300k km**	3	Reasonable for LCC but not neccesarily a value that represents LU	++	How is the reprofiling strategie related to the wheel wear, thickness of mat. taken off	Gathering field data and considering material taken off on lathe
	5	Tandem-wheelset lathe is available	2	Assumed because the best case LCC is wanted	++	Do LU depots have a tandem lather?	Visiting depots, considering in questionare for LU
	6	Lead time per wheelset 15 min	2	Assumes tandem wheelset lathe	+	Is the net time reasonable.	Experience from Siemens Northampton, Siemens consultant
Wheel exchange	7	**Interval of 1500k km** except var 3a1 (=1200k km) (~ 931.miles)	2	Is basically unknown, depends on many parameters, accurate prediction not state of the art	+++	Deriving tendency of wheel life compared to reference projects	Interviews, Calculation via parameter tool, Considering wheel wear pattern, field data and the LU reprofiling strategy Considering the wheel diameter and tread
	8	Duration 120min	3	Estimated by Siemens bogie plant	+	Wheelset overhaul process	Visiting LU's overhaul facility
	9	Material cost for a wheel is 990€	4	Depending on steel price	+	What price would apply for LU	Asking supplier Lucchini for reference prices
Wheelset bearing maintenance	10	**Exchange after 3M km**	3	Synchronised with wheel exchange	++	Is it ok to heat wheel for assembly?	Maintenance based on SKF and FAG
	11	**Overhaul/Relubrication 1500k km**	4	Synchronised with wheel exchange	++	What are reference projects	Analysing maintenance plan and relation to wheel exchange
	12	Price per part 700€	4	Price from pervious projects	+	Is this the right price?	Reference price from Siemesn Northampton and Lucchini
Wheelset axle testing	13	**Ultrasonic test 400k km**	4	Is a standard value for LCC	++	What dirves it and what alternatives are available	Considering norms, interviewing LU
	14	Duration 30min	4	Estimated by Siemens bogie plant	+		Erfahrungswerte NH, Fragebogen LU
Overhaul intervals for the bogie	15	**Interval 1200k km / 8 years**	4	Var1, Var2a1, Var2b overhaul of bogie sperate wheelset 3a1 overhaul includes wheelset	+++	Definition of overhaul?	current Siemens standard 8 years, up to now no train with 10 years out there

Table 7: List of wheelset maintenance issues to be investigated

In the table above, categories of maintenance issues have been grouped and existing values for LCC models stated. A value representative for the confidence level (C.L) related to the statement was added. Assumptions are described and questions derived that are considered suitable for improving the reliability of data. The same list was created for gearbox related maintenance issues.

	Category gearbox	Nr.	Assumption	C.L	Description of assumption		Derived questions	Planned approach
Applying for all	Visual check of gearbox mounting, oil level, leakness	16	Interval 37.5k km	3	Stated by Siemens IDT, feasibility offer study had been conducted	++	How is this values derived and can it be changed?	Questioning background, Discussion & Interaction with team BG, IDT Tobias Stärz
	Visual check of gearbox/motor for damages	17	Interval 150k km	3	Stated by Siemens IDT, feasibility offer study had been conducted	++	Can this interval be streched ?	Questioning and Discussion with experts.
	Visual Check Motor	18	Interval 37.5k km	3	Stated by Siemens IDT, feasibility offer study had been conducted	+	Can this interval be stretched? Synchronicity with gearbox check is wanted.	One of the questions for IDT
Concept 2a1	Overhaul	19	Interval 1500k km	3	Synchronity with wheel exchange / wheelset overhaul is needed	+	Can the revision be done at every second overhaul?	considering engineering specifications for a longer life cycle
	Initial oil change	20	Only 1x in life cycle	2	Adopted from gearbox LCC	+	Why is there a difference compared to concept 2b	Questioning of these intervals at Siemens IDT
	Oil exchange	21	Interval 400k km	2	Adopted from gearbox LCC		Why is there a difference compared to concept 2b	Questioning of these intervals at Siemens IDT
	Material Costs for gearbox overhaul set	22	2.069 €	3	Real price not known	+++	What are compareable material prices?	Comparison with different suppliers, projects, companies.
	Work time needed for overhaul of gearbox	23	1800 min = 30h	3	Estimation by Siemens IDT	+++	What are comparable times?	Comparison with different suppliers, projects, companies.
	Regreasing of suspension tube bearing	24	150k km	3	Values suggested bei Siemens IDT	+	Can this value be changed?	Comparison with different suppliers, projects, companies.
Concept 2b	Overhaul	25	Interval 1500k km	3	Synchronity with wheel exchange / wheelset overhaul is needed	+	Can the revision be done at every second overhaul?	considering engineering specifications for a longer life cycle
	Initial oil change	26	Only 1x in life cycle	3	Adopted from gearbox LCC	+	Why is there a difference compared to concept 2a1?	Questioning of these intervals at Siemens IDT
	Oil exchange	27	Interval 150k km	3	Adopted from gearbox LCC	+	Why is there a difference compared to concept 2a1	Questioning of these intervals at Siemens IDT
	Material Costs for gearbox overhaul set	28	1.791,80 €	3	Estimated price includes an a wanted reduction of **-15%** from projcet manager,	+++	What are compareable material prices?	Comparison with different suppliers, projects, companies.
	Work time needed for overhaul of gearbox	29	1440 min = 24h	3	Estimation by Siemens IDT#	+++	What are comparable times?	Comparison with different suppliers, projects, companies.
3a1	Same as 2b but Overhaul different	30	Revision 1200k km	3	Triggered by the wheel exchange / wheelset overhaul	+	not considered as the difference is caused by the current converter	Interval will be aligned with wheelset overhaul

Table 8: List of gearbox maintenance issues to be investigated

These research questions and issues form the approach for investigating wheelset maintenance. Field data from London Underground will be gathered and wheel life cycle and gearbox overhaul discussed in more detail.

4.1.4 Summary

The design of the four bogie concepts was discussed and their differences highlighted. LCC models will consider all train configuration variants using one of the introduced bogie concepts. The wheelset with its drive is one of the main differentiators between the designs.

Each wheelset concept has a slightly different bill of material (BOM), which creates the demand for different maintenance activities and intervals. The preventative maintenance plans cover 40 years in operation and are used to implement related material and personnel costs in the cost calculation. It is not only that different parts have to be maintained but also that the maintenance intervals are different, which means that money is not spent at the same time. This will be included when using the dynamic LCC method.

In a first sensitivity analysis the biggest cost drivers were identified for each wheelset design and priorities for further investigations defined. A list of research questions was derived from existing cost models in order to prepare data acquisition from London Underground. Field data acquisition and results from visiting London Underground facilities will be the basis for reducing uncertainty and gaining information for LCC input parameters.

The wheel life cycle and the gearbox overhaul are the most relevant research areas for this thesis because they were identified as the biggest cost factors of bogie maintenance. Firstly, however the London Underground environment and maintenance strategy of existing rolling stock shall be described.

4.2 London Underground's maintenance strategy

Knowledge about the train operating environment is essential for LCC models. Contacts with LU have been established, various interviews conducted and depots visited. The outcome of the field data gathered will be presented in this chapter. This information will help to show how the new Siemens bogies could fare over 40 years on various London Underground lines.

4.2.1 Gathering of field data

London Underground is part of Transport for London (TfL), which is a local government body. Therefore a transparency and freedom of information policy is in place. TfL was able to respond to an enquiry regarding maintenance documents, which was made via their freedom of information online tool. Further establishing contacts with local depot managers and LU employees enabled the conduction of interviews and visits to LU facilities.

All information and data provided is for academic use only. The figure below shows the information channels that enabled an insight into LU's maintenance issues for this research.

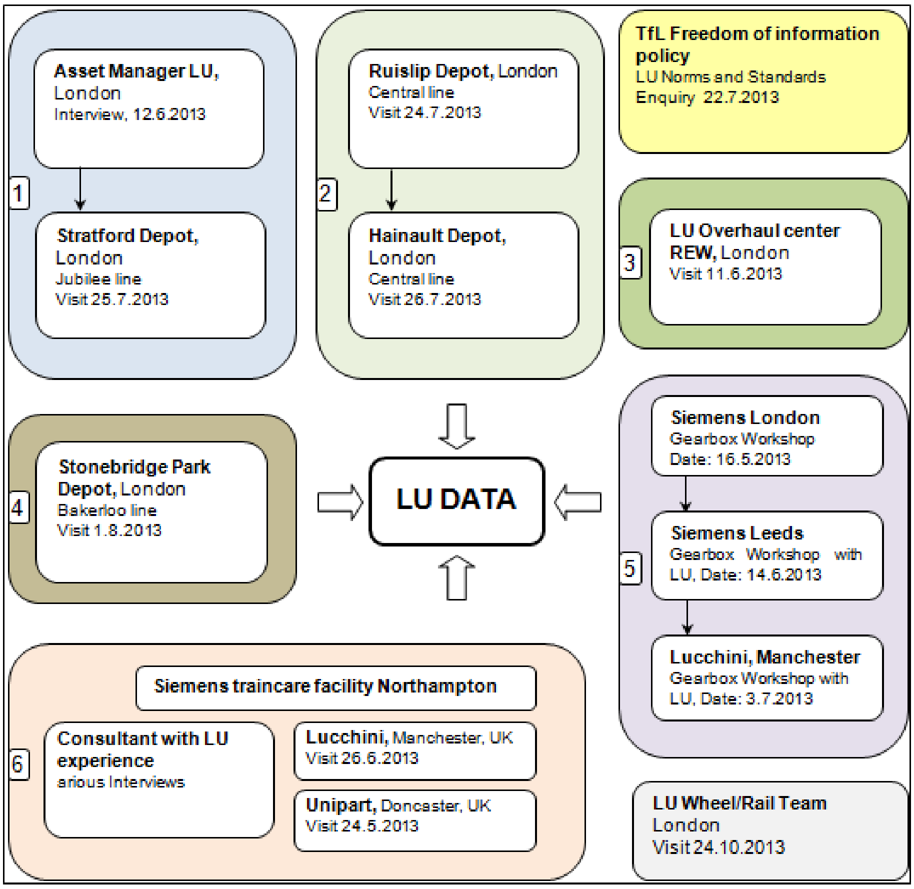


Figure 35: Information sources of London Underground field data

Channel 1: Contact with an LU asset manager was established and an interview conducted. A visit to Stratford depot (Jubliee line) was arranged to gain more detailed information about equipment and how LU maintains its tube trains on a daily basis.

Channel 2: Previous cooperation between Siemens and LU made it possible to visit Ruislip depot and to gain an impression of the maintenance regime of Central line. Here, management tools, infrastructure, used equipment and wheel wear were discussed. Later on, Hainault depot was visited for the examination of wheel wear in more detail.

Channel 3: The LU overhaul facility REW in London Acton Town was visited and the wheelset and gearbox overhaul process was discussed.

Channel 4: Maintenance regimes of older rolling stock and current wheel wear problems were discussed at Bakerloo's Stonebridge Park depot.

Channel 5: Involvement in a project concerning actual gearbox failures at LU helped in establishing further contacts and in gaining more information during workshops.

Channel 6: The maintenance expertise of the Siemens Traincare Facility in Northampton and a range of suppliers were visited. An experienced consultant who had previously worked for LU was approached at Siemens and various interviews were held.

4.2.2 Problems with generalisation of data

The tube lines operated by LU vary greatly, which makes it hard to make general valid statements in the LCC models. A few main differences between the tube lines are:

Age of trains, type of bogies, track condition, track length, track curve sizes and their distribution, operation regime with acceleration and braking control, distance between stations, ratio of over- / underground train travelling, maintenance regimes, percentage of crush loading etc.

General findings from tube lines (Victoria, Jubilee, Piccadilly, Bakerloo, Central, Northern)

All rolling stock is dedicated to specific lines and not shared between lines. Trains dedicated to a specific line are operated with the same speed and operational profile. Additionally they are nearly of the same age and supplied from one manufacturer. For maintenance planning, trains on a specific line can be considered equally. Thus it can be stated that trains and their components wear very similar, which makes it possible to set up specific preventative maintenance regimes for each line and its whole fleet. Trains are not operated after 1am and before 5am as there is only one track in place and time is needed for track maintenance.

When comparing the maintenance of trains following problems occur:

Data from new London Underground stock

Pro: Trains are state of the art and are comparable with Siemens designs in terms of technology used.

Con: These tube lines are not part of the upgrade plan and thus information can only be used indirectly.

Data from old London Underground stock

Pro: These lines are part of the upgrade plan and therefore relevant for new design concepts.

Con: Trains are around 40 years old and therefore not state of the art. It will be shown that maintenance intervals are executed more often and that installed systems cause problems that no longer apply to today's trains.

Overview about the age of different rolling stock dedicated to lines.

	Tube line	Year	OEM	Train
"NEWER" than 1995	Victoria	2009 stock	Bombardier	8 car unit
	Jubilee	1996 stock	Alstom	7 car unit
	Northern	1995 stock	Bombardier & Alstom	6 car unit
	Tube line	**Year**	**OEM**	**Train**
"OLDER" than 1996 Part of upgrade plan	Central	1992 stock	ABB Transportation	8 car unit
	Waterloo & City	1992 stock	ABB Transportation	4 car unit
	Bakerloo	1972 stock	Metro Cammell	8 car unit
	Piccadilly	1973 stock	Metro Cammell	6 car unit

Table 9: Overview of tube lines with their age, manufacturer and configuration

4.2.3 London Undergrounds rolling stock maintenance strategy

LU traditionally had 7 levels of maintenance but only the daily train preparation was seen as a fixed interval.

Level	Interval	Maintenance	Description
1	One service day	**Daily train preparation**	– Inspection requiring a functional test of specified equipment in advance of every continuous period of 24 hours that the train is available for passenger service
2	14 Days	**Examination**	– Examination and service of specified equipment, including train underside from a pit
3	36 Weeks	**Shed day**	– Inspection, service and on-train maintenance of specified equipment
4	4 ½ Years	**Programme Lift**	– Inspection, service and maintenance of specified equipment including exchange of equipment, normally involving separation of carbody from bogies
5	9 Years	**Minor overhaul**	– Inspection, service and heavy maintenance of specified equipment including replacement of equipment involving separation of the carbody from the bogies
6	18 Years	**Heavy / Major / Half Life Overhaul**	– Inspection, service and major maintenance of specified equipment involving the separation of carbody from bogies and major renewal of equipment and fittings
7	As required	---	- Replacement of equipment requiring off-train maintenance such as compressors on a time cycle independent of the parent train inspection cycle.

Figure 36: LU's traditional maintenance levels[71]

These intervals were valid for old rolling stock (source 1997) and already at that time the intervals were not rigid and rather based on the condition assessment of equipment and parts. This has further developed with newer trains in service and more up to date data will be

[71] Holmes and Dymott (1997, pp. 60-67)

presented based on visits to depots and interviews. The outcome of updated information will be presented in an overview for maintenance regimes and achieved life cycles. For validating the quality of data received a specific method was used on basis of information sources.

Rating	Description of rating	Example of Sources
+	One information source	An interview, common understanding
++	More than one information source	Two interviews, maintenance manuals
+++	Official data	Official maintenance document or statement of TfL

Table 10: Data reliability and related information sources

The table above should help to provide an understanding of how reliable data and its sources are when looking at the information in Table 11.

	Maintenance overview TUBE LINES Average values	"newer stock" >1996			"older stock" < 1996		
		Jubilee	Northern	Victoria	Central	Picadilly	Bakerlo
Mileage	Mileage per train per year (km)	160.661	159.750	185.000	145.000	134.900	112.000
	Information Source	Interview 25.6.2013	Interview 25.6.2013	TfL homepage average value	LU wheelset manual (BCV)	Interview 25.6.2013	LU wheelset manual (BCV)
	Data reliability	+	+	+	+++	+	+++
Overhaul motor bogies	Heavy Overhaul (years)	9 done in 2010	9 planned -> done 12	9 standard 12 as aim	old 4,5 new 8	4,5 for DC motor	program lift every 2,5 years overhaul 5
	Overhaul executed	1x	1x	in future	2x	-	-
	Data reliability	++	+++	+	++		++
Wheels	Reprofiling Interval (years)	1,5	3	1,5 planned (3)	2,5	1,5	1,5
	Information Source	Interview 12.6.13	Interviews, documents	Interview, picture	Interview 26.7.2013	Interview 12.06.2013	2x Interviews
	Data reliability	++	+++	++	+	+	++
	Mileage Reprofiling (km)	240.992	479.250	278	362.500	202.350	168.000
	Wheel exchange (years)	9 done 11 predicted	12 motor 16 trailer	in future	8	-	2,5 or 5
	Wheel life cycle mileage (after km)	1.445.949	1.917.000 2.556.000	in future	1.160.000	-	280.000 560.000
	Data reliability	++	+++		++	-	++
	Wheel wear pattern investigated	no	yes	yes	yes	no	yes
	Wheel diameter measurement	only on lathe	-	Measurement Rail	only on lathe	-	only on lathe
	Wheel measurement check interval	6 months using gage	6 months using gage		6 months using gage	-	6 months visually
Axle	Ultrasonic Testing standard interval (years)	250days trailer 500days motor	4,5	4,5	4,5	4,5	4,5
	Confidentially Level	+++	++	++	++	+	++
	Ultrasonic Testing equivalent mileage (km)	113.142 226.283	718.875	-	652.500	607.050	504.000
Bearings	Bearing overhaul (after years)	9	9 planned -> done 12	9	8	5	2,5
	Regreasing of Bearing (after years)	3	no regreasing	3	3	3	2,5
		Taperoller	Taperoller Timken	Taperoller	Taperoller SKF	-	Taperoller Timken
	Data reliability	++	+++	+	+++	+	++

Table 11: Overview of the London Underground tube line maintenance strategy

In this overview all components of the wheelsets are categorised and the maintenance strategy shown in relation to the six LU tube lines. Unknown values are marked with “-”. Years and mileage is used to describe maintenance intervals. Information sources and the data reliability are included for each statement.

The first row shows the annual mileage of trains based either on values given in interviews or maintenance manuals. These values are used to calculate maintenance intervals. A “+” represents a data source of one interview whereas the “+++” refers to values from a maintenance manual.

The same idea was used for overhaul intervals, which were set to 9 years as a LU standard. The older stock has a standard overhaul of 4.5 years, which was made necessary due to the DC motors. When stating the intervals above, it should be considered that all planned intervals tolerate a certain deviation. Planned overhauls are an example. They could be carried out a year later or earlier than planned. This is necessary as the overhaul of a whole fleet takes around two years. When looking at Northern line this 9 year standard was stretched to 12 years. In this particular case, monitoring techniques were used and the wheel life cycle optimised to match the new overhaul target. The number of overhauls carried out is most likely an indication of how much knowledge has been gained in the past and ideally lessons learned will be used to set the next overhaul periods.

Maintenance related to wheels is described with reprofiling intervals, the wheel exchange period and the wheel wear pattern. The life cycle is calculated on the basis of mileages stated, multiplying them with years until overhaul. London Underground, if possible, does the overhaul of wheelsets together with the bogie overhaul as it reduces the critical down time of trains. The combination of mileage and overhaul period, which can both vary, creates an increased level of uncertainty. Still, it is believed that it is representative for a possible mean value of wheel life even though not absolutely accurate. This will be looked at in more detail in chapter 5 where wheel wear, reprofiling strategies and possible life cycles are discussed.

The axle category describes the NDT testing. 4.5 years was stated as a standard interval for ultrasonic testing, which as well as MPI (Magnetic Particle Inspection) is a common method of testing axles for cracks. The Jubilee line currently has problems with corrosion developing under the wrapping cloth of the axle (moisture goes through it) and thus they are testing the axle more often as it is the most safety critical part.

All bearings used are taper roller bearings, which are regreased in stated intervals. The reconditioning or exchange of bearings is done as part of the wheelset overhaul.

4.2.4 Maintenance of specific tube lines

After the given overview, this chapter includes more specific information about the maintenance of particular tube lines and their depots.

Bakerloo line (part of DTP) Depots: Stonebridge Park

Is part of the BCV group at LU and therefore was maintained by Metronet in the past. Now it is included in the LU organisation and represents the 9^{th} busiest route. There are only 36 trains in stock but this is the maximum capacity of stabling facilities. Financial power behind the line is smaller, which explains why it is one of the last lines that do not have a lathe installed in the depot. At the only depot, Stonebridge Park, lifting equipment is available but heavy maintenance issues have to be handled at LU’s overhaul centre REW in Acton Town, London. Maintenance work is carried out over two shifts between morning and evening (no work during the night) but the second shift is often not necessary. Once work is required at the weekend it counts as overtime.

The bogie and the wheelset in use are around 40 years old and are shown in the figure below. The wheelset design follows the semi suspended principle and thus is a similar style to Siemens concept design Var2a1.

Figure 37: Bogie of Bakerloo line and semi suspended wheelset concept

Compared to new designs the bogie is quite plumb and heavy, which is related to not having simulation tools available at the time of construction. The suspension tube of the wheelset cannot be opened from the axle and has to be pressed on and off as a unit when overhauled.

The track was built during a time when the railway was not owned by the government and only owned properties could be used for tunnelling. Track data is provided in the appendix and shows that the Bakerloo line is one of the curviest. After Queenspark station, the track is owned by Network Rail for mainland train operation but also used by the LU trains. LU norms had to be matched with the railway group standards. This was done by handing in a safety case to them.

Problems caused by old technical systems, e.g. no wheel spin control are many wheel flats. Maintenance of this line is more expensive than that of the newer lines as overhauls must be carried out twice as often and the wheel life cycle in particular reaches not even half the mileage.

Central line (part of DTP) Depots: Ruislip and Hainault

At the 74km Central line, London's longest tube line, maintenance used to be done by Metronet. Metronet is now integrated in the organisational structure of London Underground and the line part of the BCV group. Ruislip depot is well equipped and has a mobile lathe, a bogie press for shimming and two lanes with cranes for lifting trains. Work takes place over 24 hours every day in several shifts.

Figure 38: Ruislip Depot and wheelset of Central line bogie

The picture on the left shows the depot and the other one on the right shows the motor wheelset with its suspension tube mounting. This mounting is in place to hold the electricity shoe and does not suspend the motor on the axle. A single stage Siemens gearbox is used and taper roller bearings from SKF as axle bearings.

During peak time (morning and evening hours) 79 trains are needed in service, whereas 69 are required for the rest of the day. All in all, 85 trains in an 8 car unit configuration are owned.

A statement was given that around 80 wheelsets are kept in stock due to the necessity of matching wheel diameters. Wheelsets of the same type can be swapped between bogies. This is done frequently to match wheel diameters within a tolerance of 3mm, 6mm and 12mm. The storage of spare bogies was outsourced to a company as the existing spare bogies had been accidently used for spare parts.

The most common failures on the train were found to be the high amount of shoe gear failures. Maintainers referred to the bad track condition, particularly the vertical deviation of the track, as a possible reason for these failures. There are further problems with the DC traction motors. DC motors are no longer state of the art but it was mentioned that at the moment no budget is available to change to AC motors, which are more widely used nowadays. Adding to these issues, water is leaking into the body shell and gearbox bearings are failing. The bearing failures occur on the pinion in the single stage reduction gearbox which has caused the overhaul of wheelsets to be necessary after 4.5 years instead of the initially 8 years planned. During this new wheelset overhaul program, important parts like wheels and axle bearings are not renewed but put back on the axle again.

Bogie and wheelset overhauls are carried out at LU's overhaul facility REW.

Piccadilly line (part of DTP) Depots: Cockfosters and Northfields

The Piccadilly line is part of LU's JNP group and used to be maintained by Tubelines. The operated trains are as old as Bakerloo line stock and have been in operation for around 40 years. Still, both tube lines have a good reputation for reliability. The drive train of Piccadilly line bogies includes a cardan shaft design and maintenance costs are high as the motor overhaul must be completed every 4.5 years. 4.5 years is also the interval for the program lift where parts of the wheelset are assessed and the decision is made whether to renew them or not.

Occurring flats on the wheels were stated as a main problem being caused by bad slippage control and no wheel spin control. The brake system has been renewed, including a new design with a levelling valve at the secondary suspension, which allows to recognise the actual loading of the train (how many passengers). This information is included in the brake control and adapts the brake force accordingly to the load when decelerating.

Jubilee line Depot: Stratford

The Jubilee line is the third busiest line and its main depot is located in Stratford, A mobile lathe and lifting lanes are in place.

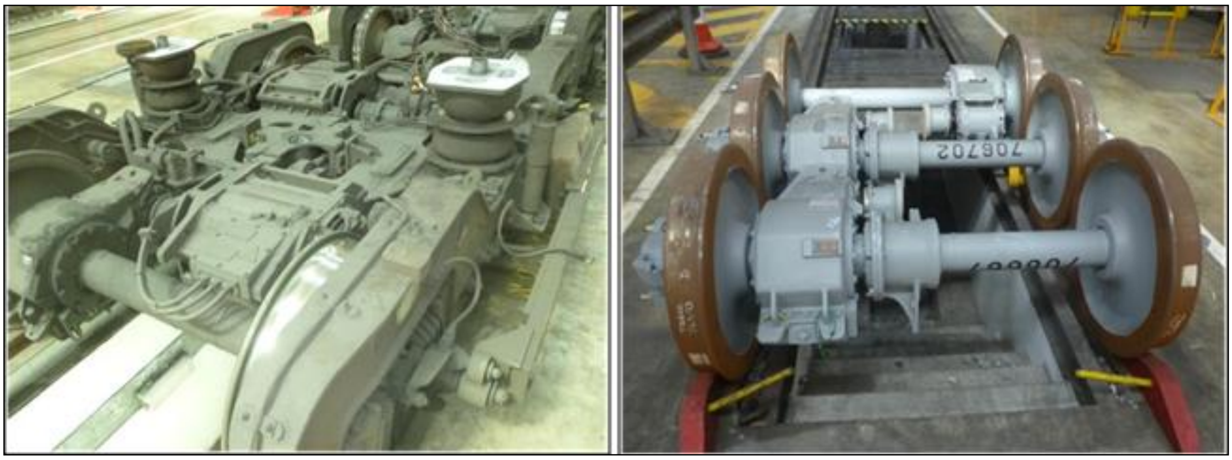


Figure 39: Jubilee line bogie and its wheelset

The bogie and the respective wheelset can be seen in the figures above. The wheelset includes taper roller bearings on the axle and a two stage reduction gearbox. The secondary suspension on the H-frame is not an air spring but a rubber suspension.

Currently there are 63 trains in the fleet and 57 of them are required during peak time.

A current problem with the wheelset at the moment is humidity coming through the glass fibre cloth wrapped around the axle. This causes corrosion on the axle, which is hard to detect due to the wrapping and requires the axle testing to be done more frequently. Ultrasonic tests on the axle are supposed to be done every 4.5 years but are currently carried out every 500 service days for motor wheelsets and every 250 days for trailer wheelsets.

The mobile lathe that is in place can be moved on rails under the train once it is lifted. At the moment the interval for reprofiling is fixed to 8.100 service hours, which is 1.5 years.

Bogie and wheelset overhauls are carried out at REW as well.

Northern line Depot: Golders Green

Northern line is London's second busiest tube line and part of the JNP group. It is the only line where trains are owned by a bank and then leased. Alstom is contracted to do the maintenance. An independent maintenance approach can be expected. The wheel life cycle achieved on its trains is remarkably high and directly related to the overhaul optimisation program of Alstom. This makes it the line with the longest maintenance intervals. It was mentioned that the interval stretching from 9 years to 12 years was achieved by including condition monitoring on the train.

It is also suggested that the flex frame bogie from Bombardier, which consists of two parts that are connected with a flexible joint in the middle, is a reason for the long wheel life.

Figure 40: Flex frame bogie design

Victoria line Depot: Northumberland Park

The Victoria line is the tube line with the newest rolling stock, using the same Bombardier flex frame bogie as the Northern line. The line is fully automated and its depot is the only depot to have a wheelset measurement rail in place.

Management techniques used in depots

Maintenance plans are individually established for every line. Planned intervals for maintenance work are specified in a time frame of service days. LU could calculate the related mileage but does not do for maintenance plans.

Job Plan	Description	Target Frequency	Generation Frequency	Warning limit	Upper limit
The relevant tube line	Exam 1	28	22	31	34
	Exam 2	182	144	190	200
	Wheel turning	540	505	560	595

Table 12: Example of LU's maintenance planning measured in service days

The operational point of view in maintenance is quite different to the theoretical approach. An initial theoretical target frequency is set for maintenance actions but is then compromised with day to day issues, depot capacity limits, stock requirements, people available, bottlenecks at certain process steps etc. Therefore, limits are set to allow a certain deviation from the original plan. The above example shows that a monthly exam is carried out every 22 service days rather than the proposed 28 days and that the 6 monthly exams and turning of wheels is done earlier than required. This already indicates the difficulty of comparing theoretical maintenance costs with those accumulating in the end.

Fleet availability is measured by trains required every day and actually trains provided. Central line for example has to provide 77 trains every day and then measures how many are available e.g. 78.

Penalty payments for not providing the service or causing delays had to be paid (based on seconds) at the time when Tubelines and Metronet were responsible for train maintenance as external companies. Now, all facilities are included in the LU organisation and these payments are obsolete. Depots feel the pressure from internal management.

Reliability is measured with the so called KMDBF (kilometre distance before failure). This value is calculated for trains over a period of 28 days and 3 months.

Lost customer hours (LCH) is London Underground's most famous performance validation tool. It calculates the time lost by customers due to delayed trains.

Work priority planning is done by setting a deadline for issues to be resolved. A priority level of 1 might refer to the requirement that the work must be done immediately and the train cannot go into service, whereas a priority value of 2 might refer to doing the work within 3 days.

TRIP At Stratford depot for example, a TRIP (Train Reliability Improvement Plan) is in place, which is related to predicting KMDBF values and related issues.

4.2.4.1 REW – LU's shared overhaul facility

Beside all the light maintenance on a daily basis it was explained that trains are overhauled approximately every 9 years. REW is London Undergrounds shared overhaul and repair facility, based in Acton Town, London. The overhaul of bogies, motors, gearboxes, clutches and the whole wheelset is carried out here. A visit to REW allowed analysing the wheelset overhaul process and discussing related maintenance issues.

The wheelset overhaul includes:

- Renewing the wheels
- Assessing axle bearings and reusing or renewing them
- Overhauling the gearbox
- Testing and measuring of all parts and the renewed assembly

REW's lead time for a wheelset overhaul is 5 days, which means it can be done during one working week. The capacity for wheelset overhauls is currently 8 wheelsets per week with a target throughput of 16 per week. By mid 2014, an increase in capacity to 32 wheelsets per week is planned.

For example, an overhaul of the Central line trains would mean heaving to overhaul around 2900 wheelsets. With 52 weeks a year and a throughput of 16 per week, this takes over three years. REW's biggest bottleneck is the testing at the end of the wheelset overhaul and thus is the limiting factor for capacity.

The process of a wheelset overhaul is shown in the figure below.

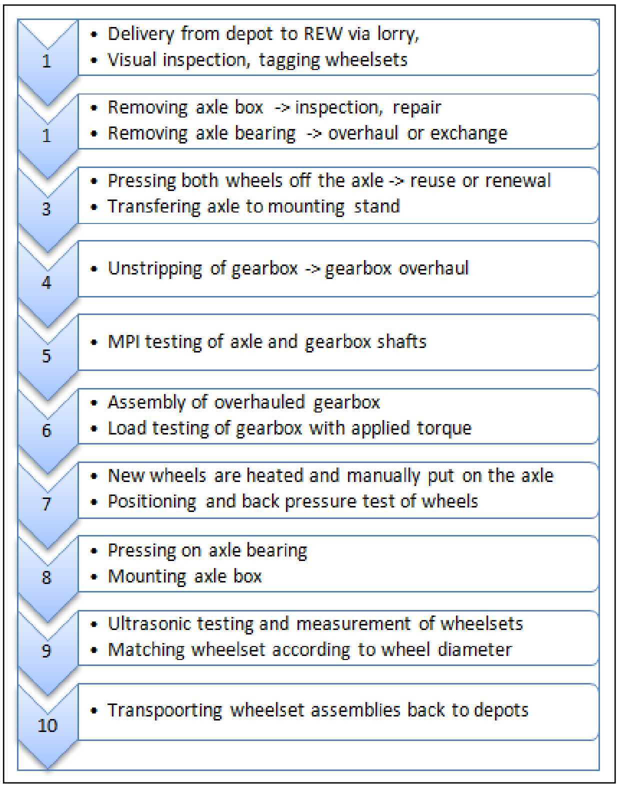


Figure 41: Wheelset overhaul process steps at LU's overhaul facility

1. The wheelset arrives by lorry, which comes directly from a depot. It is unloaded in front of the overhaul production line where wheelsets are stored, visually inspected and tagged with numbers for their identification.
2. The first step of the overhaul process is removing the axle boxes from the wheelset (if delivered with the axle box). The axle box is inspected and repaired. Following, the axle bearings are removed on a press and then washed and completely stripped. The assessment of the bearings is carried out according to the manufacturer's specifications. They will either be reused or renewed depending on their assessed condition.
3. The next step in the process is the demounting of wheels from the axle by injecting oil into them. The wheel removal requires a stable process and experience because axles can easily get scratched in the area of the wheel seat. The reason for a standard wheelset overhaul is normally the necessity of renewing wheels. But there are also cases where the wheels are just reprofiled and reused.
4. Once the wheels are off, the gearbox is accessible, oil can be drained and the housing opened. Then the gearbox bearings, seals and shafts are removed.
5. The demounted individual parts of the gearbox are investigated and include testing gears and shafts with MPI (Magnetic Particle Inspection). The wheelset axle body is checked for scratches (fretting) on the wheel seats and journals. A scrap rate of around 3% has been stated by REW. The axle has to undergo the same MPI procedure.
6. If these tests are passed, new bearings and seals are used and the gearbox is reassembled. Some gearbox designs require heat treatment for putting gears back on, others do not. An important requirement at LU is that the gearbox needs to be tested under load. A dedicated test rig is in place that measures the heat of bearings and the testing takes around 25 minutes.

7. An important fact is that wheels are heated in order to put them back on the axle. Adjustment of the wheel position can only be made while the wheels are hot. The cooling takes almost an entire day. Following, the wheels undergo a backpressure test on a hydraulic press to prove that they are mounted correctly and that they are secure on the axle. The measurement force is around 70 tons.
8. When the wheels are back on the axle, the bearings can be pressed on and finally the axle boxes as well.
9. The entire wheelset is checked again with ultrasonic testing. Finally, the completed assembly is tested for axle body run-out, tread run-out and wheel wobble. The final stage is matching wheelsets on basis of their wheel diameters.
10. After the overhaul is completed, the wheelset is delivered back to the depot where it is put into a bogie again. The whole process at REW takes around 5 working days.

4.2.4.2 Differences in the overhaul process due to proposed concept designs

London Underground does not have any experience with inboard axle bearings as none of their rolling stock is built that way. The overhaul process would change due to the fact that the wheels would have to be removed first to make the bearings accessible. But this only changes the sequence of overhaul steps and should not be a problem. During the reassembling process, axle bearings are put on the axle again followed by the wheels. The wheel mounting process includes the wheels being heated to around 250°C and being pushed on the axel manually where they sit for nearly a day to cool down. The grease in bearings is sensitive and the crucial factor for their life. It will have to be considered whether the bearings can tolerate the heat emitted from the wheel and if the grease in the bearing will stay unaffected. A heat shield will be required and the expansion and contraction of the axle diameter under the bearing must be considered. Especially in the case of hollow axles, the heat distribution on the axle and bearing might not be the same and the bearing seat might be affected.

The Siemens Syntegra concept (Var1) will require the wheelset overhaul to include the motor as it sits directly on the axle. Scrapping the axle (~3% at LU) would be more expensive because it includes the rotor and has a higher purchasing price. Var2a1, the Siemens suspension tube concept, requires another overhaul step additionally to the described one. The suspension tube has to be pressed off and on the axle and the suspension tube bearings have to be overhauled as well. But LU has experience with this type of wheelset design (see Bakerloo line). The other concepts, Var2b and Var3a1 can be overhauled with the standard LU process. The motor can be separated from the wheelset because of the coupling with the gearbox.

4.2.5 Suggestions for the LCC model

With the field data gathered and analysed, it is now possible to make recommendations for inputs into cost models so that boundaries of London Underground are considered in the calculation.

It has been confirmed that LU’s standard motor bogie overhaul for new stock is 9 years and it should be considered that LU carries out most of the bogie overhauls and wheelset overhauls together. In comparison, Siemens LCC models suggest to overhaul the bogie after 8 years and the wheelset after 10 years. The flexibility of LU's overhaul centre is limited and a time shifted overhaul might require outsourcing due to limited capacity.

A further LCC input update is the measurement interval of wheelsets, which is set to a 6 month period from an initial 4 month period. Except the Victoria line, no depot has a measurement rail in place but installing one could be part of an upgrade plan. Therefore, it is recommended that more time for measurement is allowed as it will be done manually with metal gages and/ or mobile laser devices.

The material price of wheels has a great impact on overall maintenance costs. Referring to an English railway supplier, a common wheel price was found to be in the area of around 800GBP. Therefore it is suggested to reduce the initial material price in the LCC model to 900EUR instead of the initially considered 990EUR.[72]

Wheel related maintenance and the wheel's life cycle is described in chapter 5.1. But it has been found that lathes are installed in nearly every depot and that they can be moved under the train. The Bakerloo line depot does not have any lathes.

Wheels do not show dominant flange wear and thus reach higher mileages than the low LU track quality would initially suggest. Still, Bakerloo and Piccadilly line wheels develop many flats and do not reach these high values.

A standard interval of 4.5 years is in place for ultrasonic testing. This interval decreases once the danger of failures increases, which is currently a problem on the Jubilee line. 4.5 years and an average mileage of 150k km per year suggest changing the suggested 400k km in the initial LCC models to a value more around 675k km. But this interval is considered as highly safety critical and needs approval from axle experts.

4.2.5.1 Important information for technical consideration

Life cycle costing is part of life cycle engineering, which demands that lessons learned in maintenance should be used to improve technical designs. During interviews at LU it became clear that no large scale track renewal at LU is planned because it won't directly help to improve the current capacity shortage and the availability of the service. Interview partners suggested designing bogies in a way that they are able to cope with track irregularities and do not design them to the very limit of safety. This means finding the optimal balance between weight reduction (safety limits), which means reduced energy consumption and on the other hand system reliability (robustness). Gathered data shows that Bombardier's flex frame bogie (Northern line) achieved the longest maintenance intervals and wheel life cycle.

As the proposed design concepts include hollow axles and inboard bearings, it should be mentioned that all axles at LU are solid and use conventional outboard bearings. These outboard bearings are all taper roller bearings, either from SKF or Timken. According to LU's standards, it is a requirement to manufacture all axles with cold rolling, including a specified groove to release stress. Until now, fibre class cloth wrappings around the axles were

[72] Siemens supplier contract with a wheel manufacturer, 2013

compulsory to protect them from sparks. A statement from a LU manager indicated the desire to change this in order to avoid current problems with humidity coming through the cloth, which causes corrosion on the axle. A new approach for axle protection is being looked into.

Another important insight was given at REW, where the overhaul process was analysed. It has become clear that LU has been using heated treatment for mounting wheels ever since, which seems to be the common way of doing it in England.

4.2.6 Summary

As a government-run organisation London Underground has the “freedom of information policy” in place, which made it possible to visit several depots, conduct interviews and obtain specific norms and standards. The described information was gathered from several visits to LU depots and interviews conducted with LU managers.

The chapter has provided an overview of the London Underground maintenance strategy for all tube lines. Data reliability measures were added for rating the quality of information source. Further to this, particular tube lines and their depots were discussed in more detail. The overhaul process at the London Underground overhaul facility, REW, was described and the management tools in place briefly explained.

Finally, suggestions were made for input parameters in the created LCC models and for considerations regarding the technical design concepts. This has helped to follow an approach that considers London Underground’s train operating environment and maintenance strategy.

General questions for modelling LCC costs were answered in this chapter but the two main questions remain. One is the search for a potential wheel life cycle and the other one the gearbox overhaul cost. The next chapter will discuss these issues in more detail as they have been identified as relevant cost drivers and differentiators between design concepts.

5 Analysing wheelset components

This chapter describes the most important components of wheelsets and their related maintenance requirements. Wearing of parts depends on their environment and their functions. Life cycle costs over 40 years strongly depend on the length of component life cycles and the necessary maintenance.

For train owners and maintainers the required safety levels in train operation should be achieved in the most cost effective manner. The design of parts can influence the maintenance regime and therefore the costs.

The wheelset overhaul is the cost driving factor and is influenced by[73]:

- Wheel diameter
- Wear and deterioration of the bearings
- Age and condition of the bearing lubrication
- Wear of gears
- Damage to any of the components
- The need to check the axle body with a magnet particle inspection (MPI)

Wear and deterioration in wheelsets is heavily influenced by the annual distance travelled, proportion of braking and acceleration, the extent of curvature on the respective line, its design and so on. The wheel life cycle and the gearbox overhaul have already been identified as the cost driving factors and will be discussed in further detail.

5.1 Wheel life cycle

The wheels are parts on the wheelset that require the earliest exchange and are the trigger for the wheelset overhaul. The wheel's life cycle therefore defines the amount of overhauls required during the train's life. This chapter explains wheel wear and identifies a potential wheel lifetime for the four Siemens design concepts. Various estimation approaches were followed and reference data from London Underground was collected in order to compare the results.

5.1.1 Wheel wear

Wheels are designed to have an infinite life but formation of flats, martensitic heat affected zones on the running surface (crack propagation), flange and tread wear as well as plastic deformation are influences that limit the wheel life cycle.[74]

An exact prediction of wheel wear and the related life cycle is not state-of-the-art as it requires foreseeing the future and having detailed information on numerous parameters. Despite the difficulty faced, the wheel life cycle is crucial for train operators' economic considerations and is therefore critical for LCC statements in a bid. London Underground defines its own norms and standards, which includes wear limits on the wheel profile. Wheel profiles describe the shape of

[73] London Underground Ltd. (2010)
[74] Cassidy (2001, p. 289ff)

the running surface on the wheel, which defines their dynamic drive behaviour. London Underground has specified the wheel profile to be a LT5[75] shape for new trains. The profile and wheel measurement points with its definitions are shown below.

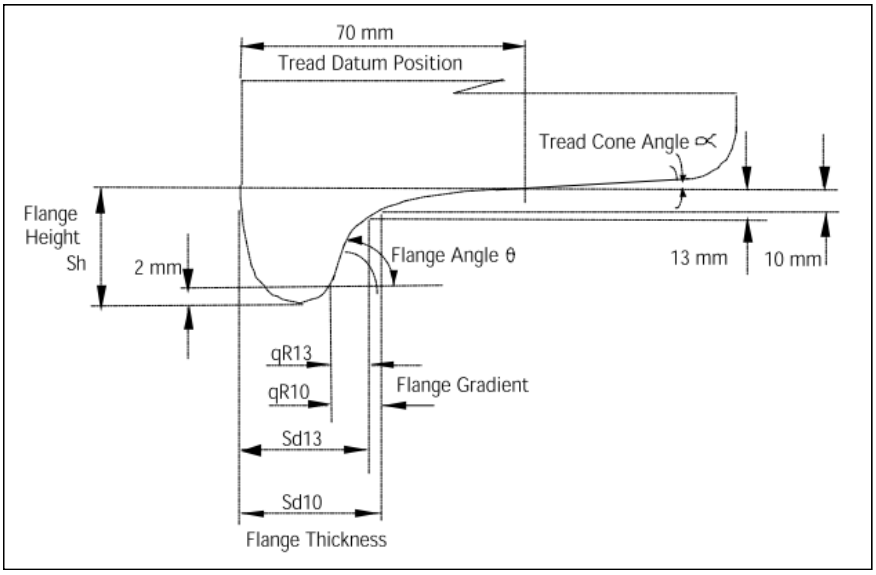


Figure 42: Wheel profile reference parameters according to E6347 A3 standard[76]

The tread cone angle is important for drive dynamics but will be subject to wear and the profile will wear during operation. Therefore the height “Sh” but also the flange thickness “Sd” are measurement points for ensuring the wheels functionality. The flange gradient “qR” is a measurement parallel to the axle and the wheel diameter is always measured at the tread datum position. Acceptable limits of wear and permissible tread damage are stated in LU’s norm E6347 A3.

Tread wear, flange wear, run out, plastic deformation and their interdependencies are the main damage mechanisms. Hence they are the limiting factors for the life of train wheels which is measured by mileage reached in operation. Another outcome of Dr. Kaempfer’s research was that wheels used in middle Europe in terms of their usual geometrical standard (flange thickness, flange height, QR value and gauge) tend to follow a linear abrasion relationship over mileage under the assumption of constant conditions.[77]

Wheels have a defined diameter when they are new and are designed in a way that train maintainers are able to turn off material from the diameter in order to restore the profile once it has worn. A functioning profile is important as vehicle dynamics which are related to passenger comfort, track wear and derailment safety are influenced. Figure 43 explains how a new wheel diameter is reduced over mileage until the scrap size diameter is reached and the wheel exchange is required.

[75] Referring to wheel geometry, LUL engineering drawings: Ref No. 92667
[76] London Underground Ltd. (2003, p. 6)
[77] Kämpfer (2005)

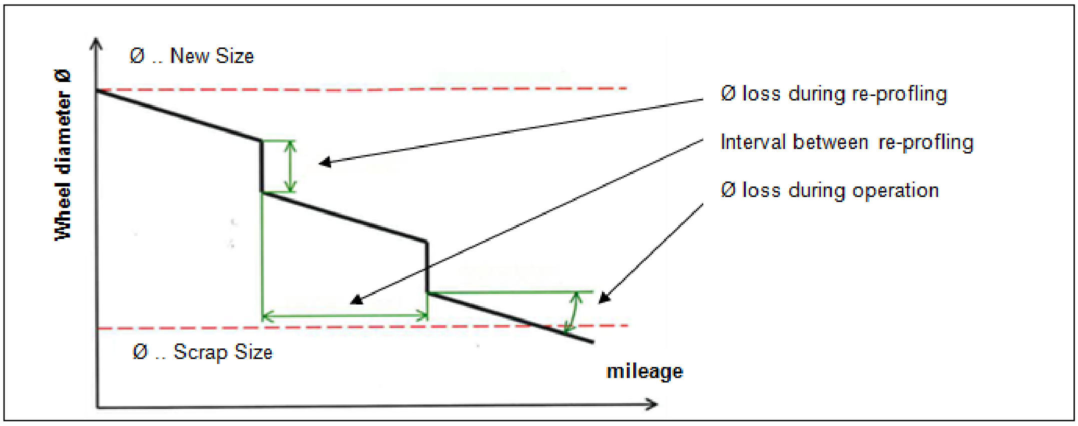


Figure 43: Qualitative development of a wheel diameter over mileage[78]

Once in operation, wear decreases the diameter (linearised) on the running surface. Once wear limits are reached (e.g. flange height limit) or a defined mileage has been travelled (see reprofiling strategies), material on the wheel is turned off on a lathe to restore the profile. The wear pattern shown below is a determining factor for the amount of material removed from the diameter. Flange wear commonly occurs when wheel flanges contacting the rail head, which happens mostly during curving.[79] Reprofiling a wheel with flange wear will result in a smaller number of reprofiling events and thus a shorter wheel life cycle.

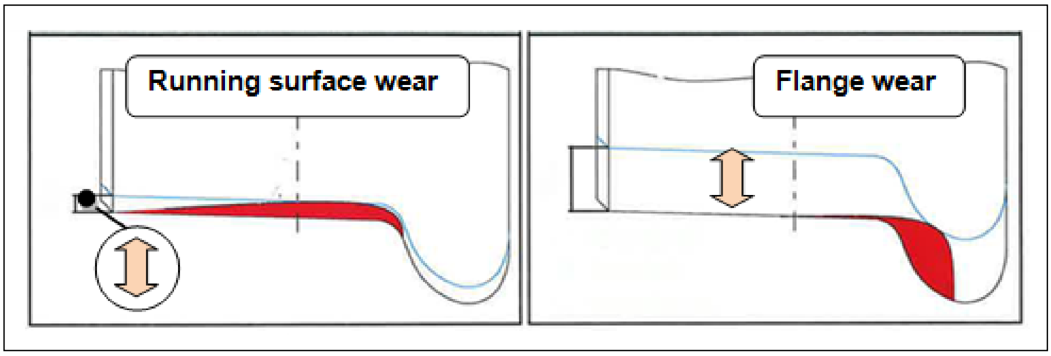


Figure 44: Metal turned off during reprofiling in relation to wheel wear patterns[80]

When the dominating wear occurs on the running surface wear, also referred to as tread wear, the following reference value for metal turned off can be given. An increase of 1 mm flange height (radial) can be related to an additional 1 mm radial material cut off with the lathe. This means running surface wear of 1mm requires approximately 2mm to be turned off. On the other hand, dominant flange wear can be alternatively associated with a ratio of 1:3.[81] These values should not be seen as absolute, they are rather given to support the understanding of wear and related reprofiling. The additional material that is removed also depends on how big and deep running surface cracks are. Still, the logical conclusion that the occurrence of flange-wear leads to a shorter wheel life is justified.

[78] Kämpfer (2005, p. 27)
[79] Cassidy (2001, p. 289ff)
[80] Kämpfer (2005, p. 28)
[81] Interview with Siemens wheel expert, Graz, 2013

The picture below gives an idea about how wheel profiles are measured with a metal gauge and wheel wear patterns are identified by the train maintainer. Measurements are either done with electronic laser devices (e.g. Calibri) or manually with metal gauges. In the picture below flange wear can be identified, whereas the running surface has not worn much.

Figure 45: Worn wheel profile compared with a new profile shape on a metal gauge[82]

5.1.2 Reprofiling strategies

Reprofiling was already described as the removal of wheel material from the diameter and is either condition based maintenance or preventative, which includes the planning of events. Condition based means that profiles are restored once measurements require the metal removal for a safe train operation. On the other hand preventative reprofiling means that wheels are cut after a defined mileage.

Condition based reprofiling increases the down time of a train as reprofiling events are more distributed and are not planned. This strategy requires regular measurements where “go/no-go” decisions are made. On the other hand it is likely to create a longer wheel life as no metal is turned off if not necessary.

In comparison, planned reprofiling intervals (e.g. 300k km) make it easier to manage machine capacities, logistics and train down time. It should be considered that wheels which could have gone for longer are cut as well. Still, some additional condition based reprofiling is inevitable once wheel defects like flats, cracks, pitting, etc. are too big.

So both strategies can hardly to be realised without each other. Condition based wheel turning will still require some operational production planning and on the other hand preventative reprofiling will require some condition based wheel turning due to occurring wheel defects.

Reasons to reprofile include the restoration of worn flanges and worn treads, the removal of flats, removal of cavities and cracks, and the removal of plastically deformed material on

[82] Siemens photo database

wheel.[83] Four main reasons are further involved in the condition of a wheel tread: safety; ride characteristics; noise pollution and cost.[84]

The OEM will suggest measurement and reprofiling intervals in LCC models and include clauses for which boundaries the statements are valid. Here, wear predictions influenced by the design of wheelsets, bogies and trains are used as basis for the statement.

As the design itself covers only some of the wear influencing parameters, the train maintainer is free to change these intervals once trains are in operation and hard data is available. New intervals are then defined based on the experience and measurements made on trains in operation and also the capacities of wheel lathes.

A typical reason for setting shorter preventative reprofiling intervals is when wheel damage is frequently recognised (e.g. wheel flats). These issues were investigated during visits to London Underground depots.

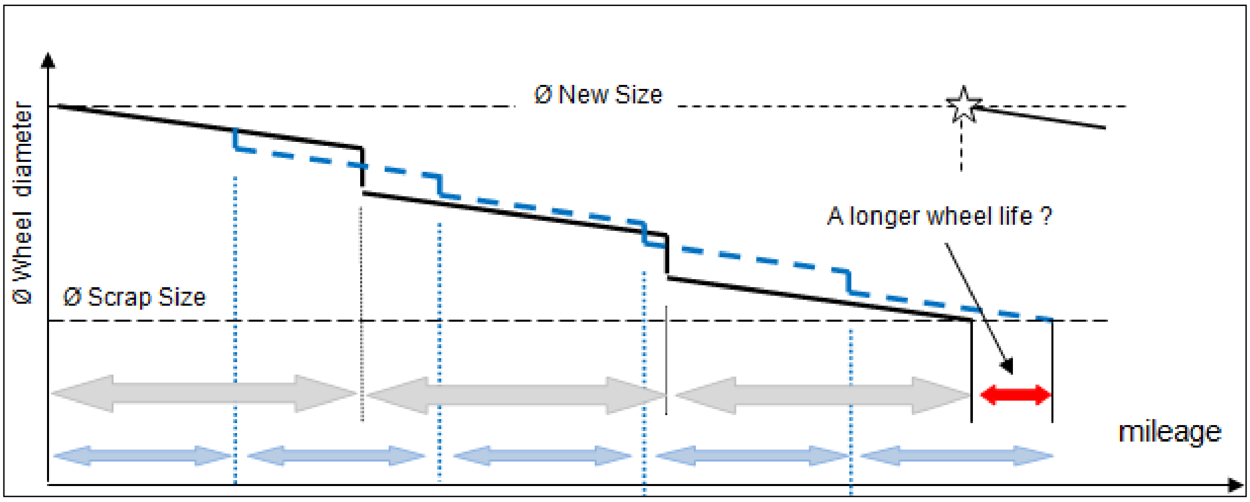


Figure 46: Reprofiling intervals and diameter loss during a wheel's life cycle

The picture above shows a possible relation between chosen strategies, in particular the length of reprofiling intervals and the related total wheel life cycle. Thus not only the tread thickness (difference new diameter to scrap size) is important for optimising the wheel life cycle but also the mileages before wheels are machined and the diameter turned off.

Wheel wear, drive dynamics, constraints from rail due to damage like RCF (rail contact fatigue), capacity of lathes etc. will influence the decision of the maintainer. The important question for cost models is now to define intervals that will represent reality as well as possible. This is important because a long wheel life cycle will reduce costs for the maintainer and will make the LCC offer more attractive.

The British RSSB (rail safety and standards board) concludes in a white paper that there is no benefit in more frequent re-profiling when the predominant wear pattern is flange wear. It is

[83] Cassidy (2001, p. 291f)
[84] McEwan (2000, p. 1f)

suggested to delay reprofiling for as long as possible in this case. The bespoken research included vehicle dynamic simulations, consideration of wheel geometrics and field data.[85]

RSSB funded another research published in 2013 that investigates reprofiling intervals in terms of whole life costs. The optimum for the turning interval was calculated to be 160k miles and it is concluded that more frequent preventative reprofiling would result in higher costs and a lower life cycle. Only turning wheels on condition would relate to lower costs but this advantage is offset due to increased down time of trains.[86]

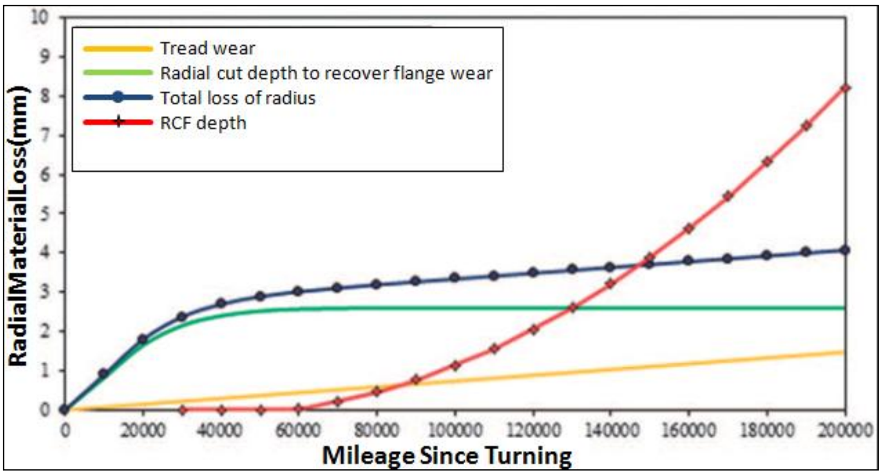


Figure 47: Radial material loss during wheel turning[87]

The figure from the research shows that RCF (rolling contact fatigue) increases exponentially with mileage, flange wear increases sharply after the reprofiling event but is flattening out later on and tread wear increases linearly. Therefore it is necessary to analyse the existing wheel wear pattern of London Underground trains in order to consider the best strategy. This will be carried out in the following chapters.

5.1.3 Approach followed for estimating a potential wheel life

The approach to be followed in order to find out what a possible wheel life cycle could be is shown below.

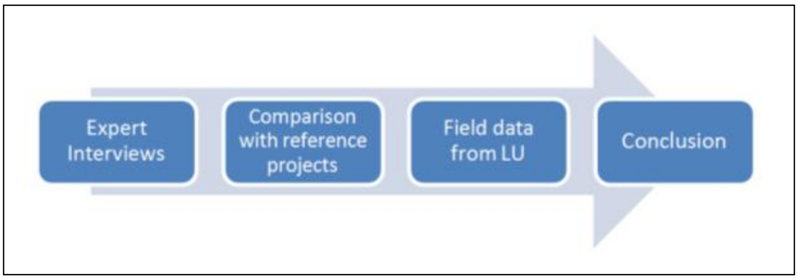


Figure 48: Approach followed for wheel wear prediction

---

[85] Rail Safety and Standards Board (2008)
[86] Bevan, Molyneux-Berry, Mills, Rhodes, and Ling (2013)
[87] Bevan et al. (2013p.10)

First, interviews with were pursued with experts at Siemens in Graz. Following, a more objective tool was established to include as many parameters as possible and compare results with similar underground trains. Finally results were compared with real life data from London Underground and the wheel wear pattern investigated. Each of these steps will be described in more detail.

5.1.4 Wheel life cycle prediction with interviews

Various interviews were conducted with experts from Siemens bogie plant in Graz. Due to the complexity of wear mechanisms and lack of data regarding the environment of London Underground, estimated values vary greatly.

One question that needs to be asked however is whether a certain bias of interviewees exists due to their professional involvement with the topic and their opinion about related problems that come with wheel life prediction. It is suspected that people working in the area of warranty would tend to produce more conservative statements whereas people in sales would probably prefer the idea of a long wheel life cycle. Offering the customer a life cycle that is long and therefore related to low life cycle costs would more likely lead to a contract being awarded.

Following information was provided to the interviewee:

Track data, reference values of the Siemens metro platform “INSPIRO”, ratio of tunnel to surface operation, rain fall, leaves on the rail, diameter wheels and the tread thickness. The figure below shows the statements that were given based on the aforementioned background information.

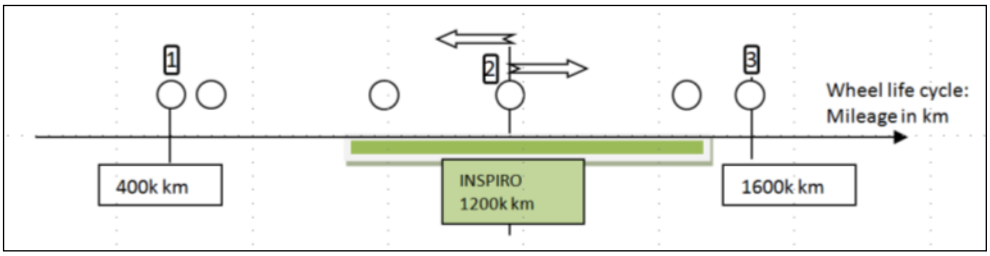


Figure 49: Estimated wheel life mileage from several railway experts

In order to understand the context of these statements the ideas behind the most extreme statements will be described.

<u>The idea behind interview 1, statement 400k km – lowest value</u>

The interviewee summarised LU’s environment as demanding and used the lower end of the *Inspiro* platform reference values, which is 800k km as benchmark. The person further included the fact that the proposed wheel is smaller and the additional tread volume on the rim is smaller by the factor 2. It was judged that in the worst case, the wheel life cycle could be around 400.000km.

<u>The idea behind results of interview 2, statement 1.200.000km</u>

The same information was given here but the interviewee related the statement more to the optimised bogie designs with a reduced wheelbase and more flexible wheelset guidance. The idea was that new designs had been improved compared to the existing *Inspiro* design. Further considerations about the environment and the smaller wheel persuaded the interviewee to conclude that the positive effects of the state-of-the-art designs might be reversed by the small wheel diameter and stated 1.200.000km as a realistic figure.

<u>The idea behind results of interview 3, statement 1.600.000km</u>

This interviewee estimated that the smaller wheels result in other positive effects like a smaller wheelbase, which was judged as more important than other influencing factors. The person had a rough idea about London Underground's current wheel life cycles and knew that reprofiling intervals were comparatively long.

Other interviews brought up values in between the two extremes. More and more information was provided during the interviews. It was recognised that the influence of the interviewer increased and that the influencing parameters became too many and could not be quantified properly for reliable statements.

Conclusion Interviews

The established interviews showed the vast difference in estimations and that the prediction of the wheel life is a highly complex problem. Stating wheel life cycle values is required in LCC models and can create controversial opinions. The lowest value stated in the interviews would cause the maintainer to change the wheels 15 times during the train's life cycle whereas the most optimistic statement would only require the wheels to be changed 3 times in the space of 40 years. This difference would cause wheel life cycle costs to differ by the factor 5 which is a deciding factor for the whole LCC. The topic has been given increased attention as the wheel is the main cost driver in wheelsets over the life cycle (chapter 5).

Interviews are not a reliable method for estimating the wheel life cycle as the interviewer himself should not need to decide which interviewee provided the most trustworthy information. A statistical approach calculating the mean value was not followed either, however a more advanced approach was chosen with the aim of implementing as many wheel wear influencing parameters as possible and benchmarking results with comparable projects.

5.1.5 Wheel life predictions using a "parameter tool" and reference projects

The basis of this investigation is a collection of around 45 parameters that were identified (by Siemens) as wear influencing. These parameters are assigned to weighted wear categories which had been developed by Siemens wheel experts. Quantifying all parameters and taking into account the weight of the categories enables the calculation of a wear value. This wear value was already calculated for reference metro projects from the Siemens "Inspiro" platform and allowed for a comparison. Information about the vehicle configuration and field data from London Underground was acquired and implemented into the calculation.

Table 4 shows the eight wear categories and their weighted influence on wheel wear. All 45 wheel wear influencing parameters are assigned to one of the categories.

Category	Weighting (%)
Wheel properties	4,5 %
Rail properties	5,5 %
Train application profile	19,5 %
Material between wheel and rail	10 %
Drive and braking system	15 %
Train concept	15 %
Track	18 %
Maintenance strategy	1,5 %
Environment	11 %

Table 13: Wheel wear influencing categories and their impact[88]

The table shows that it would be misleading if one were to relate wheel wear to wheel properties only. It is suggested that parameters like wheel profile, diameter, material, etc. which are assigned to the category "wheel properties" only influence wear by around 5% in total. The biggest influences are stated to be caused by the train application profile which includes braking and acceleration values (19.5%). The track including the radius of curves contributes to around 18%. The train concept and its drive and braking system are considered to be main aspects as well because each category accounts for 15% of the result.

Therefore it is essential to consider the train as a system and the environment of operation. A view focussed solely on wheelsets would not be sufficient for the prediction. This increases the complexity and the amount of data required for the research.

Nevertheless, parameters from each of these categories are listed in the next table and are the basis for a benchmark with reference metros in operation. A so called "Wear value" is calculated which then can be related to the already acquired mileages of the reference wheels. This wear value is representative for how strained the wheels become during operation.

[88] Siemens expert judgement, pair-wise comparison method used

Parameters assigned to their category						
Wheel properties	**Material between wheel and rail**	**Drive-/Braking System**	**Train concept**	**Rail properties**	**Train application profile**	**Track**
Wheel geometry (profile & diameter)	Friction Modifier (running surface, acoustics)	Mechanical braking concept (tread brake)	Wheel base (mm)	Rail geometry	Mode of operation (Single or mixed operation)	Quality of track (geometry deviation) measured track position
Wheel material (incl. coating)	Sanding, used amount of sand per wheel	Braking concept (Blending, what force on which system)	Design of wheelset guidance (incl. active wheelset guidance elements)	Gauge of track	Time table (number of acceleration and braking cycles) per train/100tkm	Stiffness of track
Tread thickness	Wheel flange lubrication and track lubrication	Wheel spin / slippage control	Undamped masses	Rail material	Train control (AZ fast braking - way of braking)	Distribution of cross force
Rotatory mass of wheelset	Used amount of lubricant per wheel	Traction usage (train configuration, ratio of motor to trailer bogies)	Axle loading	Wear pattern of track	Distance between stops	Cant / Banking
Wheel gauge	Sand in the environment	Type of drive (cardan shaft, electrical,..)	x-Factor (torsional rigidity of bogie incl. active throwning elements)	**Environment**	Altitude difference (Hill, valley)	Distribution of curves
Maintenance Strategy	Proportion of wet and dry track	Drive- / braking control (electric, pneumatic, diesel-hydraulic,..)		Area / climate	Distance per year	
Wheel measurement periods	Proportion of clean to dirty (leaved) track	Allowed differences of wheel diameters in (mm)		Surrounding temperature	Distribution of loading	
Reprofiling strategy		Accuracy of slippage prevention system		Mechanical influences		

Table 14: List of wear parameters allocated to their weighted category

These 45 wheel wear influencing parameters can further be categorised into parameters related to the train configuration and its technology (green fields) and those that are representative for operational environment (blue fields).

A comparison with vehicle and track parameters that are influencing wheel life from P.D.Cassidy's point of view was made and the compared parameter list can be found in the appendix, Table 36.[89]

[89] Cassidy (2001, p. 296)

Introducing the method behind calculating the wear value

The idea behind this Excel based tool is to evaluate each parameter with a value between 0.1 and 1.0, where 0.1 is the best case and 1.0 the worst. The Excel parameter tool was programmed to calculate arithmetical mean values for each category. This has the advantage that not all 45 parameter necessarily have to be known and unknown values can be considered as neutral.

Example: In category "Train concept" one can find the parameter "design of wheelset guidance". The stiffness of the wheelset guidance influences curving behaviour of the wheelset and is also related to hunting and similar drive dynamic phenomena. A value of 0.1 would be given if the design were to have active wheelset guidance (best case). On the other hand it would get a value of 1.0 for very stiff wheelset guidance (worst case). In the particular case of using a "hydro bush" it is given a value of 0.3 as the stiffness of this element changes with the train velocity and nearly behaves like active wheelset guidance. This approach makes it possible to compare projects with contrasting wheelset guidance by taking into account their design difference in the parameter evaluation.

This again should highlight the difficulty that was faced in interviews as it was not possible for the interviewees, even experts, to consider more than 40 different influences and combinations in a personal estimation.

All parameters were given a value between 0.1 and 1.0 and the sum was produced for each category. Utilising up the above example again this could look like: "Category: Train concept" - wheelbase = 0.2, wheelset guidance = 0.3, axle loading = 0.6 and x-factor = 1.0 and would result in a category sum of 2.1. This category sum is finally multiplied with the weight of the category (table.) which in this case would be 0.15 ("train concept" category).

This procedure was reproduced for each category in order to create their respective sums. The category sum is then multiplied by the weight of the category. Adding the weighted sums brings up the so called wear value, which is used as a comparison measure with reference projects.

$$\text{Wheel wear value} = \sum_{k=1}^{7} [\frac{1}{n_k} \sum_{i=1}^{n} x_{ki} * \text{wheight}_k] * 100$$

Formula 3: Calculating the wear value (own formula)

k... what category, seven in total

n... amount of parameters in category k

x... parameter evaluation in category k

Siemens metros operating in Nürnberg, Praha and Bangkok already provide historical real life data for wheel life cycles and have been assigned a wear value. Relating their wear value to the acquired wheel life cycles provides the necessary reference for the comparison with the new London Underground concepts.

However, existing reference projects initially had to be adjusted to the new calculation method (arithmetic mean values). The implementation of the newly developed LU concepts also required a change in the lower and upper limits for certain parameter ratings in order to be able to include them.

Three main data types that were required for the analysis:

- Field data (information about track, climate etc.)
- Operational data (information related to the operation of the train such as braking, etc.)
- Vehicle specific data (related to components, systems and technology used)

Various visits to LU depots and various interviews produced data for most of the parameters involved. There is still a lack of information about specific operation schedules at LU, but these missing parameters were included and labelled as neutral.

Results parameter tool

The table below shows the results for the category sums and wear values calculated. This allows for retracing influences and their source for each application.

Comparison of wheel wear

Parameter group	Average from Senitivity analysis	Underground trains								
		VAG U2 Nürnberg	VAG U3 Nürnberg	Metro Prag	BTS Bangkok	MRTA Bangkok	LU VAR 1	LU VAR 2a1	LU VAR 2b	LU VAR 3a1
Wheel properties	4%	0,63	0,63	0,57	0,43	0,43	0,63	0,63	0,63	0,63
Rail properties	6%	0,50	0,53	0,53	0,63	0,63	0,63	0,63	0,63	0,63
Application profile	19%	0,40	0,40	0,60	0,56	0,56	0,46	0,46	0,46	0,46
Material in Wheel/Rail conta	10%	0,43	0,43	0,35	0,45	0,45	0,48	0,48	0,48	0,48
Drive-/Braking System	15%	0,44	0,44	0,39	0,60	0,66	0,44	0,48	0,48	0,51
Train concept	15%	0,50	0,50	0,50	0,55	0,55	0,33	0,35	0,40	0,40
Track	18%	0,55	0,55	0,50	0,58	0,45	0,60	0,60	0,60	0,60
Maintenance Strategy	1%	0,45	0,45	0,45	0,50	0,50	0,80	0,80	0,80	0,80
Environment	11%	0,50	0,50	0,50	0,70	0,60	0,60	0,60	0,60	0,60
Sum wear value		4,4	4,4	4,4	5,0	4,8	5,0	5,0	5,1	5,1

Parameter group	weighted factor representative for wheel wear								
	VAG U2 Nürnberg	VAG U3 Nürnberg	Metro Prag	BTS Bangkok	MRTA Bangkok	LU VAR 1	LU VAR 2a1	LU VAR 2b	LU VAR 3a1
Wheel properties	2,6	2,6	2,4	1,8	1,8	2,6	2,6	2,6	2,6
Rail properties	2,8	3,0	3,0	3,5	3,5	3,5	3,5	3,5	3,5
Application profile	7,8	7,8	11,7	10,9	10,9	8,9	8,9	8,9	8,9
Material in Wheel/Rail conta	4,1	4,1	3,4	4,4	4,4	4,6	4,6	4,6	4,6
Drive-/Braking System	6,7	6,7	5,9	9,2	10,1	6,8	7,3	7,3	7,8
Train concept	7,6	7,6	7,6	8,4	8,4	5,0	5,3	6,1	6,1
Track	9,9	9,9	9,0	10,4	8,1	10,8	10,8	10,8	10,8
Maintenance Strategy	0,6	0,6	0,6	0,7	0,7	1,1	1,1	1,1	1,1
Environment	5,6	5,6	5,6	7,8	6,7	6,7	6,7	6,7	6,7
Sum wear value	47,8	47,9	49,2	57,0	54,6	50,1	50,9	51,7	52,3

Table 15: Wear value of LU design concepts compared to reference projects

The chart below shows the sum wear value of several underground trains compared to one another. A high wear value indicates that a shorter wheel life cycle is more likely.

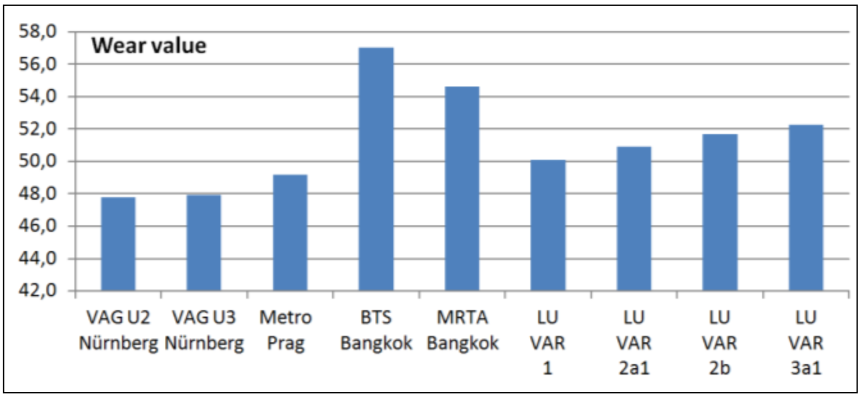


Figure 50: Benchmark of wear values calculated

The wear value is dimensionless and can be related to known wheel life cycles. Utilising Praha metros as a reference, its wear value of 49.2 can amount to 1700k km wheel life. This would give 34.55k km mileage per wear unit. Applying this value to the LU concepts allows for one to predict their wheel life cycle mileages. The wheel wear value can be sub-divided into a vehicle based and operation based factor.

Wear of wheel	VAG U2 Nürnberg	VAG U4 Nürnberg	Metro Prag	BTS Bankog	MRTA Bangkok	LU VAR 1	LU VAR 2b	LU VAR 2a1	LU VAR 3a1
Vehicle based influence	17,0	17,0	15,9	19,4	20,3	**14,4**	**15,2**	**16,0**	**16,6**
Operation based influence	30,8	31,0	33,2	37,6	34,3	**35,7**	**35,7**	**35,7**	**35,7**

Table 16: Proportion of wear value based on the vehicle designs and the train operating environment

The values "vehicle based wear" and "operation based wear" can be explained as follows.

Vehicle based wear factor

All parameters that can be related to the configuration and design of the rail vehicle are summed up within this value. The new LU design concepts Var1 to Var 3a1 relate to vehicle based wear values that are lower than those of compared reference trains. It highlights the fact that the designs are state-of-the-art and optimised with a focus on wheel wear.

A few examples shall be given as to why the wear value is different for the design concepts. LU Var1 shows the lowest wear value. This is due to a more flexible and bigger design of the wheelset guidance and based on the calculated Tgamma[90] value between wheel and rail. Var1 and Var2a1 also have a shorter wheel base of 1.6m compared to 1.8m of Var2b and Var3a1 which is beneficial for curving. Further parameters include that Var3a1 is the only concept with a grouped motor control which requires matching wheel diameters when reprofiling, which results in a lower wheel life.

Operation based wear factor

All non-vehicle based parameters can be related to the operation regime of the train and the environment it is operating in. LU's environment is demanding with the biggest wear factors created by the heavy schedule, amount of starts and stops, percentage of crush-loaden operation, the track quality and so on. Of course values are the same for all LU design concepts. Compared to reference metros in operation, the London Underground is a highly demanding environment.

Tendency of wheel life cycle mileage

Finally using the wear values and related reached wheel life cycles of the compared projects allows a prediction of wheel life for the four LU concepts. The next table shows predicted values in relation to which reference project is used.

[90] Calculated work due to friction between rail and wheel

Reference Projects							
VAG U2 Nürnberg	VAG U4 Nürnberg	Metro Prag	BTS Bankog	LU VAR 1	LU VAR 2a1	LU VAR 2b	LU VAR 3a1
		1.700.000 km		1.668.939	1.640.781	1.616.538	1.598.820
1.200.000 km	1.200.000 km			1.145.463	1.126.137	1.109.498	1.097.337
			1.000.000 km	1.138.274	1.119.069	1.102.534	1.090.450
		Ranking		1ST	2nd	3nd	4th

Table 17: Predicted mileage based on wheel life cycle and wear value of reference projects

Here, a problem with accuracy can be immediately identified in the tool. When using metro Praha as reference for LU variants, the predicted values are higher than when using metro Nürnberg as reference.

Comparing the LU concepts to one another shows that the differences are not significant and that they stay in a range of 100k km.

Accuracy and problems

A tool created to give differing results depending on the reference used is normally considered wrong. However, this is only true if there is a claim to be precise. This is not a requirement of the analysis as the aim was to identify a trend. But what causes the inaccuracy? The mileages used from reference metros could be biased. Data received for wheel exchange intervals show a lack of information regarding the reasons for the exchange; it does not necessarily mean that the wheels were at the end of their possible life. Other economic, such as factors like down time costs of the train and defined overhauls can dictate an early exchange of wheels, which would cause the bias. When considering a whole train, single wheels do not wear with the same rate and it strongly depends on their position on the train. Therefore all concerned values are considered as mean values representative for an average value of all wheels mounted.

Furthermore, different reprofiling strategies and especially wheel wear patterns influence the whole life cycle.

Conclusion parameter tool

Results based on reference values differ from 1100k km to 1700k km. This is a deviation of 600k km and gives an idea of how accurate the tool can be. The approach should therefore only be seen as supporting method when predicting life cycles and does not guarantee a certain value. But these statements are a corner stone in life cycle cost models and the way in which values are predicted needs to be agreed with the customer.

The comparison has also shown that Var.1 is the concept with the highest predicted wheel life cycle. This is due to the bigger hydro bush being used und thus more flexible wheelset guidance, the small wheelbase and the motor control that independently operates wheelsets. But the difference to the other LU design concepts is only 100k km at maximum and therefore not so big.

It is further suggested that the tread thickness in combination with the reprofiling strategy has a further dominant influence that is not considered with the parameters included. Therefore especially the wheel wear pattern has to be considered and predicted for the developed design concepts.

Extended wheel life cycle considerations

The following investigation considers the tread thickness and the reprofiling strategy for the wheel life cycle. Wheel wear patterns could be predicted using MKS (multi body simulations) of the train, including precise track data and the operational profile and so on. A comprehensive literature review and the descriptions of a wheel wear simulation tool can be found in Kaempfer's dissertation.[91] But in an early concept stage a lack of precise track data and knowledge about defined train operating profiles from a potential customer often does not allow the use of this simulation method.

Hence, field data from LU trains was gathered to gain real life understanding about the actual wheel life cycles, their wear patterns and the applied reprofiling strategy.

5.1.6 LU wheel reference data

Trains, tracks, operation profiles, etc. are different across tube lines and so are the wheel life cycles. Managing wheel life cycles at LU involves three main players in the organisational structure. These are depots, the REW - overhaul facility and the centralised engineering department. Most depots have lathes installed and execute wheel reprofiling independently but still need to send their wheelsets off to REW for overhauls. REW has the equipment for replacing wheels and also does the reprofiling for depots that do not have a lathe installed. At the start of 2013, LU additionally set up an engineering team for wheel rail interface management. The team manages wheel and track maintenance with the ultimate objective of optimising whole life cost whilst ensuring compliance to safety standards. All aforementioned facilities have been visited and wear patterns, reprofiling strategies and life cycles will now be further discussed for a few tube lines.

5.1.7 Wheel wear pattern

Wheel wear patterns show how and where the wear takes places on the wheel. This provides information about operational conditions and can be used for optimisation measures on the wheel. Targeted track lubricating and lubrication on the wheel surface are examples for optimisation measures. Further, reprofiling strategies can be planned and the metal thickness defined that is removed on the lathe. Wear profiles will be discussed and shown for Victoria, Northern, Central and Bakerloo lines.

Victoria line

The Northern and Victoria lines run the newest trains which have a Bombardier flex frame bogie installed. This bogie type is flexible due to its two bogie frame halves that are connected in the

[91] Kämpfer (2005)

middle with a joint. Victoria line trains also have implemented automatic train control and operate with acceleration values of 1.3m/s^2 and deceleration values of 1.14 m/s^2. The next picture shows a wheel profile on a trailer wheelset measured with a “MiniProf” device.[92]

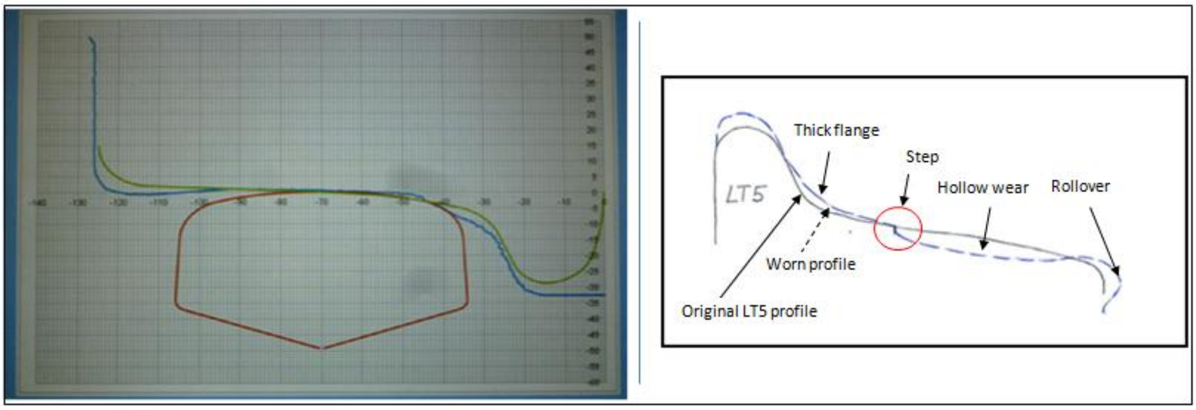


Figure 51: Victoria line trailer wheel and its wear pattern

The wear pattern shows that hollow wear of the wheel creates a “step” shortly before the slightly thickened flange. The planned interval for reprofiling was planned to be 3 years but due to the “step” developing this was not reached. This type of profile deformation becomes unacceptable when it is bigger than 2mm in size and currently triggers the reprofiling event to be after 1.5 years. The problem occurs mainly on trailer car wheels and LU experts suggest that it is subject to differing friction areas on the wheel’s running surface. It is a common method to lubricate wheels with flange lubrication sticks and running surface lubrication sticks. Both are mounted on the train to reduce friction on the wheel profile and therefore wear. This means the installation of lubrication sticks at the wheel flange (LCF, Low coefficient of friction) and (HPF, High positive friction modifier) for the running surface causes the wheel to wear unevenly over the profile. But not all wheelsets are lubricated and the position where the LCF and HPF devices are installed is shown in the figure below.

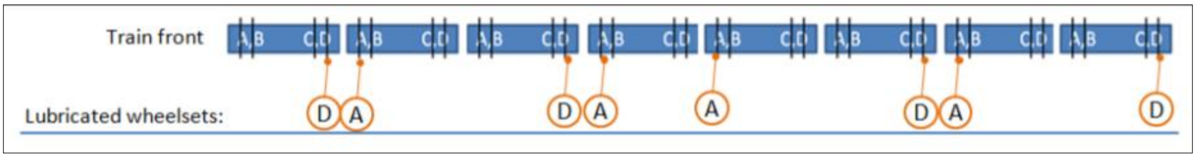


Figure 52: Wheelsets on Victoria line trains where LCF and HPF lubrication sticks are installed

LU wheel experts see the positioning of these friction changing elements as a key element for optimising the wheel wear and wheel life cycle.

Northern line

The installed flex frame bogie from Bombardier (also in Victoria line trains) is assumed to align very well on track curves which limits wear to a small area on the running surface. The wear pattern looks similar to those of the Victoria line but without developing a problematic “step”. A material flow towards the flange and wheel edge can be identified on worn wheels. On the small

[92] E. Teixeira, London Underground, Hainault depot, received 07/2013

contact area, wear creates a hollow profile which has to be corrected on the lathe when reaching LU limits.

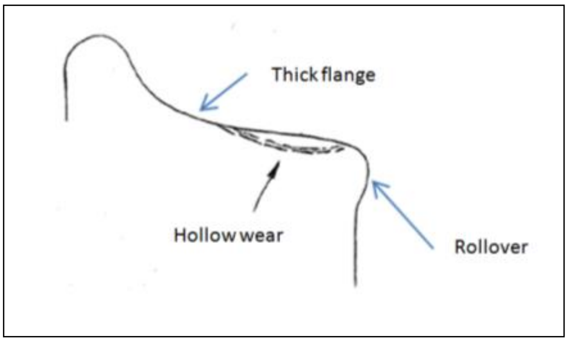


Figure 53: Typical wheel wear pattern on Northern line wheels

Due to the state-of-the-art trains, wheels last for 3 years before reprofiling is necessary and are exchanged every 12 years during the bogie overhaul.

Central line

Central line trains are operated via automated train control (ATO) as it is used on the Victoria line. This control system brings with it the disadvantage that trains accelerate and brake at the same points on the track which causes "squats" on the rail. Wheels also do not show flange wear as dominant wear pattern. A measurement with a metal gauge at Ruislip depot showed that hollow wear is the main reason for reprofiling.

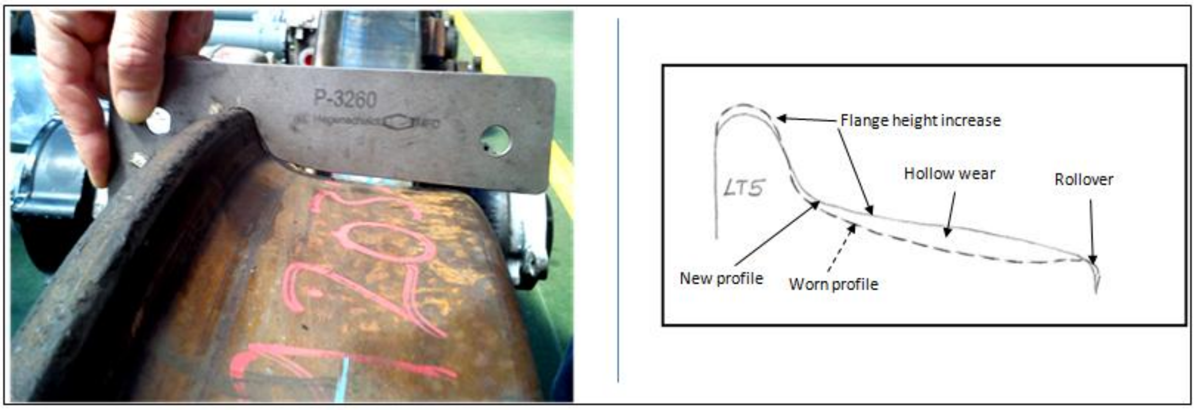


Figure 54: Central line motor wheel and its wear pattern

Bakerloo line

Bakerloo line trains are now more than 40 years old and do not have wheel spin control or wheel slippage control systems installed. The train is operated manually which results in many wheel flats during autumn when train drivers have to get used to changing weather conditions and leaf fall. The lower adhesion between wheel and rail causes the driver to brake more strongly which causes wheels to lock up. The old and heavy bogie itself is not comparable to nowadays new bogies and neither is the wheel wear pattern and wheel life cycle. The track includes many curves in the centre of London as it was only possible to build under properties which they owned.

A visit to Stonebridge park depot showed that wheel wear strongly differs depending on the wheel position on the train and it was apparent that flats are a major problem. Wear occurs on the wheel flange, inside and at the back of the wheel. Reprofiling is executed every 1.5 years whereas the overhaul program lift is executed every 2.5 years. During this event a “go or no go” decision for the wheels to be exchanged is made. This is the decision if the wheel is used again based on the diameter.

A problem related to surface greasing is that little metal pieces are absorbed into the grease. This grease aggregates on tread brakes and has an abrasive effect on the wheel surface. The wear profile created by this mechanism can look unusual which is shown in the picture below.

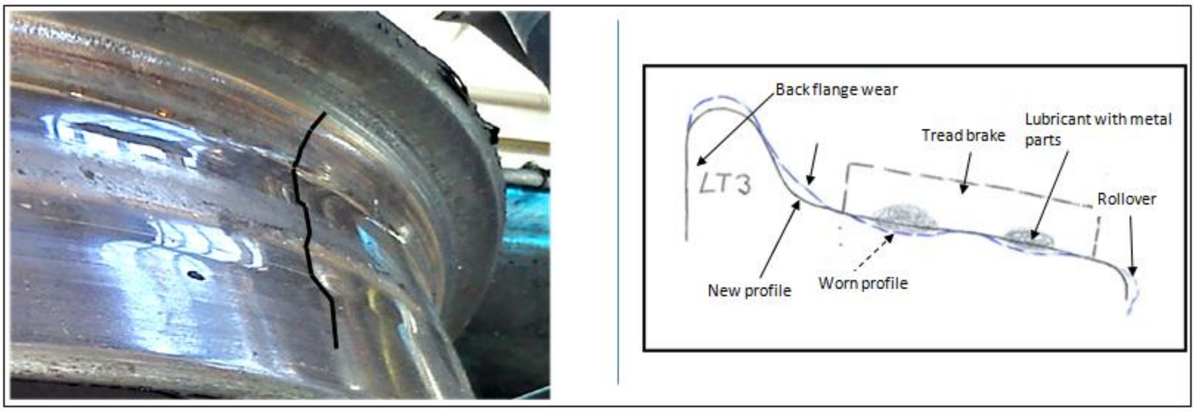


Figure 55: Bakerloo line wheel and its wear pattern

It should be mentioned that the wear profile shown has a great impact on drive dynamics, passenger comfort and track damage.

More limiting factors of wheel life

All of the wear patterns that have been introduced progress over mileage and require reprofiling sooner or later. Another wheel life limiting factor is not caused by wear but rather by wheel diameter tolerances. This means that after each reprofiling event, the smallest wheel dictates the diameter of other wheels and material is lost additionally to wear. A reason for small tolerances is the requirement that the electricity shoe stays in contact with the electricity rail. Therefore they are tighter on motor cars and greater on trailer cars.

Motor wheelsets	Between two axles in a bogie	Between axles of two bogies
Motor wheelsets	3 mm	6 mm
Trailer wheelsets	6 mm	12 mm

Table 18: Wheel diameter tolerances between axles and bogies – example Central line trains

Beside the values stated above, LU standard E 6347 A3 specifies the allowed wheel diameter deviation between the left and right wheel on the axle with 5 mm.

Each train unit has two bogies installed and each bogie contains two wheelsets. Therefore 8 wheels have to be matched with each other when considering a train unit.

The visit to Ruislip depot showed that around 80 spare wheelsets are kept in stock in order to match diameter sizes. A fleet of 85 trains each with 8 car units and again 2 bogies with 2 wheelsets – means that 85*8*2*2 = 2720 wheelsets are in the fleet. Central line has 80 additional wheelsets in stock which represents a spare cover of 3%.

The speed of trains is controlled by multiplying the wheel radius with its angular speed (sensor on every axle). With the new bogie design concepts each motor wheelset is either independently controlled or two wheelsets grouped and managed from one power converter. When each motor is supplied by its own dedicated power converter the wheel diameters between wheelsets do not need to match. An independent control allows a different angular speed of wheelsets and thus can balance out the different diameters. The limit that is still given is the defined space envelope of the train that is not allowed to be violated due to the tunnel size.

The Siemens bogie Var3a1 is the only design variant that has one power converter for two motor wheelsets which means their wheels still have to match within a tolerance. With the other designs the wheelsets are controlled independently. This difference is taken into account with a 20%[93] smaller wheel life cycle due to material loss on the lathe. This is largely influential on overhaul intervals and considering a 1500k km life cycle would be 1200k km instead.

Track/Wheel interface

A damaged wheel profile can destroy rail quite rapidly. A bad track quality on the other hand can increase wheel wear. These interactions are subject to the topic wheel/track interface and only the optimisation of the whole system is economically sensible.

Both, the flat bottom rail with a UIC56E1 norm profile and the bullhead rail with a LT3 norm profile are installed at LU. The rail material is specified with R260, which is a type of steel that is suitable to tolerate a R9T wheel material. The main problem with LU rails is a damage type called “squats” and can be understood as a “bruise” on the rail caused by wheels. To reduce this type of damage rails with wider profiles are locally replacing the old ones. The so called Tgamma value is an important indicator for damage created on rails. It is the friction work that is created between wheel and rail due to the sliding of the wheel and forces in the contact area. The simulation program “Vampire” is used at LU’s newly established wheel/rail interface department. This department has provided the track data provided in the appendix.

Overview of LU wheels

Various LU facilities were visited and the acquired information was then summarised. A rating for data reliability is included in order to describe related information sources.

Rating	Description of rating	Example of Sources
+	One information source	An interview, common understanding
++	More than one information source	Two interviews, maintenance manuals
+++	Official data	Official maintenance document or statement of TfL

Table 19: Confidence level rating of data dependent on its sources

The next table gives an overview and insight into the 6 LU tube lines and related values for their wheel properties, reprofiling strategy and life cycle.

[93] Estimation

LU WHEELS	"newer stock" >1996			"older stock" < 1996		
	Jubilee	Northern	Victoria	Central	Bakerloo	Piccadilly
Wheel properties						
Profile	LT5 P-3260	LT5 P-3260	LT5 P-3260	LT5 P-3260	LT3	LT3
Diameter: New size	770	770	740	700	790	790
Diameter: Scrap size	707 Motor 690 Trailer	710 Motor 690 Trailer	700	650	710 Motor 700 Trailer	710 Motor 700 Trailer
Tread thickness	63/83	60/80	40	50	80/90	80/90
Last turning diameter	-	725	-	665	-	-
Wear/re-profiling motor wheelsets						
Diameter loss mm/year	4 mm	1,5 mm	2 mm	2,7 mm	-	-
Data reliability	++	++	+	+	-	-
Diameter loss/100k km	1,56 mm	0,59 mm	-	0,86 mm	-	-
Reprofling intervals (years)	1,5	3,0	1,5	2,5	1,5	1,5
Data reliability	++	+++	++	+	++	+
Diameter loss in operation	-	4,5 mm in 3y	4 mm in 1,5y	-	-	-
Diameter removed on lathe	-	12 mm	10 mm	25 mm	25 mm	-
Data reliability	-	+++	+	+++	+++	-
Nr. of reprofiling events likely	-	3	-	1	2	-
Wheel life cycle in years	9	12	in future	8	2,5/5	-
Yearly mileage	160.661	159.750	-	145.000	134.900	112.000
Wheel life cycle in mileage	1.445.949	1.917.000	in future	1.160.000	560.000	-
Data reliability	++	+++	-	++	++	-
Lathe installed in depot	Y: mobile	Y:mobile	Y:mobile	Y:mobile	no	no

Table 20: Wheel related data of London Undergrounds tube lines

All wheels are made of steel with a comparatively high hardness of R9T which refers to a carbon content of 0.6%.[94] The wheels' profile is a LT5 or LT3 shape. LT3 is only used at the two oldest fleets, the Bakerloo and Piccadilly lines. Wheel diameters vary between 790mm and 700mm and therefore provide differing amounts of tread thickness for reprofiling. It was found that LU does, if possible, the wheelset overhaul together with the bogie overhaul. The standard interval is 9 years for the newer lines but the Northern line overhaul was even stretched to 12 years. On the other hand, 4.5 years is still the standard for the older trains used on Bakerloo and Piccadilly lines. Following this, the yearly mileage of trains was multiplied with their overhaul period. This leads to a kilometre based value for the wheel exchange period.

In more detail, wear in terms of diameter loss per year was investigated and the number of planned reprofiling events stated. The metal removed on the lathe during a reprofiling event was found to be between 10mm and 25mm on the diameter. Reducing the diameter by 25mm on the lathe is an indication that flats occur but also flange wear could require the high amount of material removed. All values are mean values and subject to the stated degree of uncertainty.

Concerning the wheel wear pattern it was recognised that with the new lines no extensive flange wear occurs at new LU trains, which is a plausible explanation for some of the high

[94] Cassidy (2001, p. 295)

wheel life cycles reached. It is very clear that new trains cannot directly be compared with old trains as the technology implemented is more advanced. The highest values are reached at bank owned Northern line where wheel exchanges were carried out after 12 years, which is equivalent to approximately 1900k km train travel. Alstom has been contracted to maintain the trains which resulted in commercial optimisation programs regarding maintenance. This and the flexible bogie frame, which turned out to be wheel friendly, are possible explanations for the extraordinary wheel life cycle achieved. The author suggests that when a company has a maintenance contract and there is no measure in place to control related track wear, cost optimisation regarding the wheel life cycle could simply neglect track wear.

Conclusion LU wheels

Track data that is provided in the appendix. Despite most of the tracks are relatively curvy no dominant flange wear was recognised. New rolling stock, like that of the Northern line, have reached high wheel life cycle mileages, old ones on the other hand, do not achieve even half of this mileage. Values from around 500k km up to 1900k km were then calculated.

Siemens bogie design concepts and their related wheel life cycle

The life cycle cost model uses a value of 1500k km and 1200k km as parameter for the wheel life cycle parameter. 1500k km represents an overhaul period of 10 years for the wheelset. An investigation of the suggested 1500k km with the best reprofiling scenario of LU is used to check the feasibility of this life cycle.

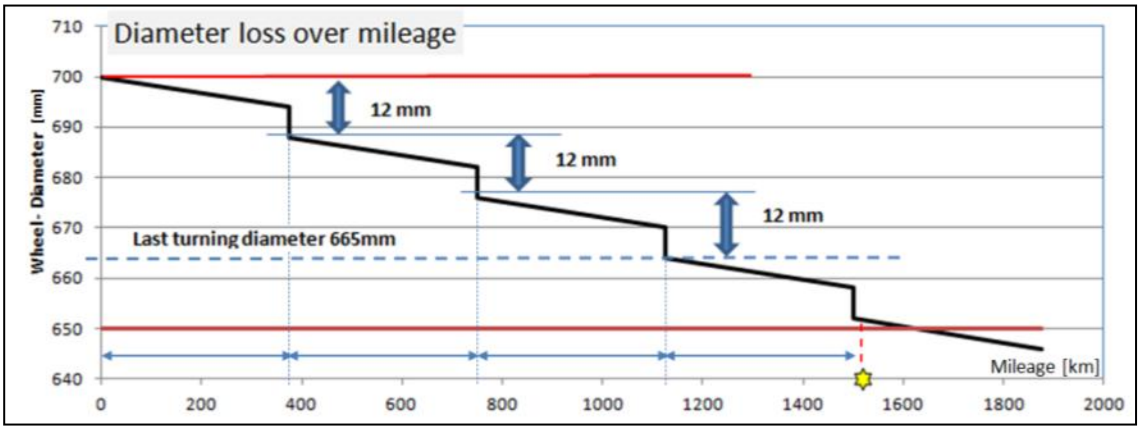


Figure 56: Siemens 700mm wheels, diameter loss over life cycle

The wheel starts with a new size of 700mm in diameter, wears linearly during operation and has to be reprofiled on the lathe to restore the profile. This analysis showed that only 3 reprofiling events are likely when using LU's best subject (Northern line) with a reprofiling cut of 12mm on the diameter. 3 reprofiling intervals will be included in the LCC models in order to consider LU's current maintenance strategy.

The relevance of the tread thickness is clearly supported by the analysis of possible reprofiling events. The considered wheel is comparatively small and begs the question why a smaller wheel should be chosen in the first place. The next table provides a quick overview of the positive and negative effects related to this choice.

Effects of smaller wheels	Positive effects	Negative effects
	Lighter wheels result in a lower undamped mass on the axle and less energy consumption during operation	Smaller tread thickness does not allow extensive reprofiling
	A smaller wheel requires less space and a lighter bogie frame is feasible	Wheel has to rotate more often for the same mileage
	The smaller wheel also allows a shorter wheel base which means better curve alignment of the bogie	Higher contact pressure on rail and wheel
	More space can be utilised in the train	
	A lower centre of gravity of the train resulting in smaller forces on wheels during curving – less wear	

Table 21: Positive and negative effects of a comparably smaller wheel

Reduced undamped masses are a factor for track wear which is one of LU's priorities. The short wheelbase is an advantage for wheel wear considering the curvy LU tracks, as it aligns to the track more easily. Reduced rotational masses due to smaller wheel diameters require less power from motors which is considered as beneficial for energy consumption. The lighter bogie frame and the lower centre of gravity further reduce the dynamic forces on the wheel.

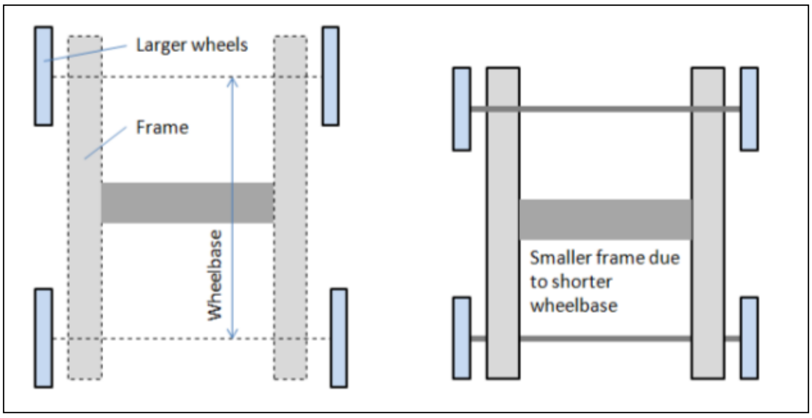


Figure 57: Shorter wheelbase and related mass reduction

Reducing the wheel diameter and wheel mass leads to a smaller mass moment of inertia. Hence traction moment needed is smaller and the electric traction motors can be built slightly smaller. This leads to reduced energy consumption. The torque that is required for just accelerating the wheels can be simplified and written for a cylindrical body as:

$$M = J * \ddot{\varphi}^2 \quad \text{with} \quad J = \frac{1}{2} * m * r^2$$

Formula 4: Motor moment for wheels required and mass moment of inertia

The motor moment (M) required to accelerate a mass moment of inertia (J) strongly depends on the wheel radius as it influences the result with the power of 2.

One who has travelled with the deep tube lines in London knows that due to the old tunnel system space in the carriages is very limited. The Underground transport system is working at its full capacity and space for passengers in the trains is an important criterion.

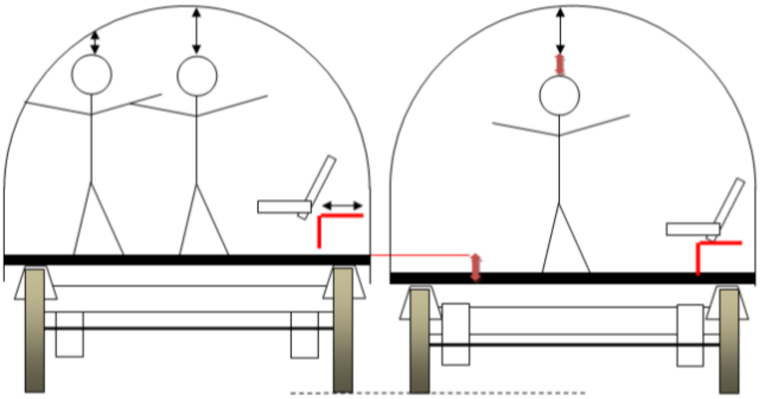


Figure 58: More space for passengers due to smaller wheels

Smaller wheels increase the space in the cars but the height of platforms still has to be met and sets a limit to this benefit.

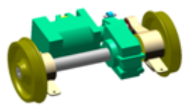
Analysing the effects of different wheel diameters shows that cost factors like energy consumption and track wear etc. are related to the design of a wheelset. Therefore it is justified to allow higher life cycle costs from maintenance as long as the overall benefit is greater. Whole life cycle cost models, developed by Siemens in Vienna, attempt to include these interdependencies. Finding the cost optimum for the entire train operation system will be the target of customers.

Influence of the wheel life cycle on maintenance costs

The analysis of the reprofiling strategy has shown that a reduced wheel diameter and a small tread thickness can lead to a shorter wheel life. A cost sensitivity analysis (Var2a1) was established to see the economic impact a shorter wheel life cycle would have on wheelset maintenance costs. The analysis could be used consider potential trade-offs in the design.

LCC Scenario1:
Wheel life cycle 1.500k km
Lubrication of bearing 1.500k km
Exchange of bearing 3000k km
Gearbox Revision 1.500k km

LCC Scenario2:
Wheel life cycle 1.200k km
Lubrication of bearing 1.2k km
Exchange of bearing 2.400k km
Gearbox Revision 1.200k km



LCC Szenario 1 – wheel life 1500k km	LCC Szenario 2 – wheel life 1200k km
Wheelset + Gearbox (40 years)	Wheelset + Gearbox (40 years)
Maintenance costs:	Maintenance costs:
405.000 EUR	532.000 EUR
Difference:	**+ 127.000 EUR**
	= 131% of Szenario 1

Figure 59: Impact of wheel life on wheelset maintenance costs

The sensitivity analysis of wheelset maintenance (net costs) was conducted to show the difference between a possible wheel-life of 1200k km compared to 1500k km. It was already described that the wheel life cycle triggers the overhaul and that the other components of the wheelset are changed with the wheel renewal due to down time minimisation. It can be seen that a cost difference of 127.000€ is inherent to the interval change which is an increase of 31% in wheelset maintenance costs considering the introduced 9 car train concept.

The operational point of view from the maintainer

Theoretical maintenance costs do not represent costs that actually occur for the train maintainer. LCC models for bids are normally created for one train and used to demonstrate the maintainability of particular designs. But maintenance is carried out on a whole fleet of trains, which includes more issues to be taken into account for related costs. Figure 75 shows that LU wheelsets will have to be overhauled at different times due to differing wheel diameters, which is shown in Figure 75 in the appendix. Further, the capacity of depots and infrastructure is one of the most decisive criteria once a fleet is in operation. In addition, the allowed down time of trains, availability of equipment and bottlenecks in maintenance facilities are important. But it is extremely difficult to include all these influences in bid appraisals, particularly when the amount of required data from a potential customer defines the biggest obstacle. An example is given considering the exchange of wheels on a fleet, which automatically represents wheelset overhauls as well.

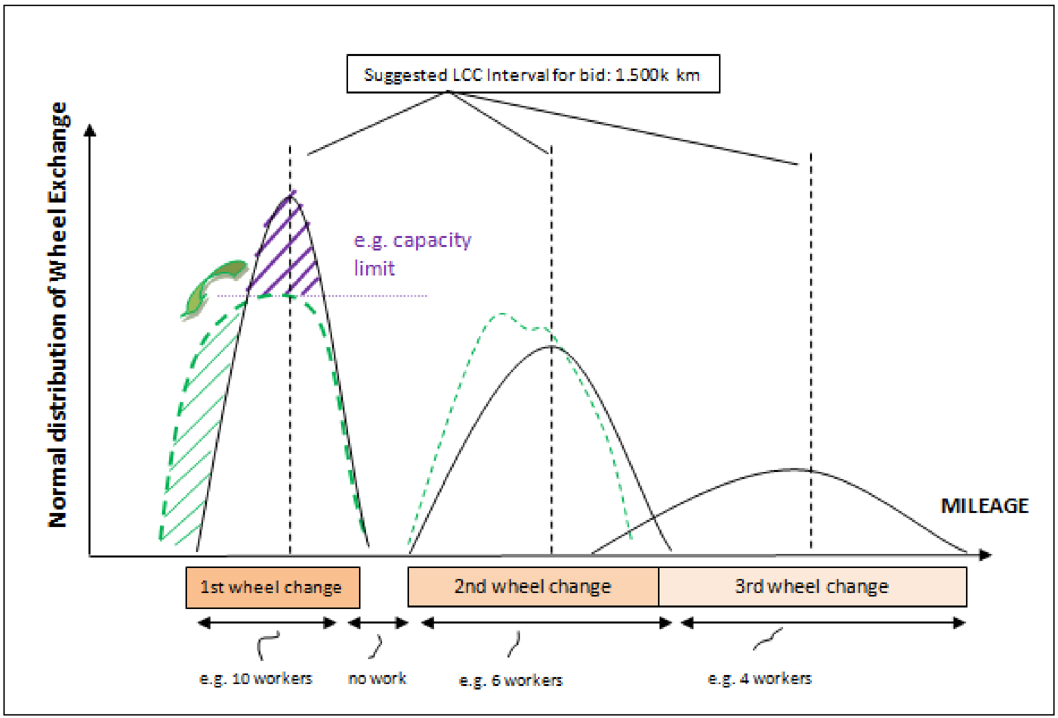


Figure 60: Possible normal distribution of wheel exchanges considering a fleet of trains

LCC models for maintenance costs in a bid appraisal are based on predicted intervals for the wheel exchange to calculate costs. This means that no normal distribution regarding the wheel exchange is included. But as already explained in the maintenance chapter, the exchange of parts is subject to failure rates and wheels might not wear equally on all trains. The figure above shows that a small amount of wheel exchanges will be required earlier (mileage) but the main amount of exchanges will be concentrated. Furthermore, certain wheels will have the potential to last longer than others. This creates a normal distribution around a mean value, which is 1500k km in the figure above. This mean value was already analysed and predicted. Including a normal distribution also means that the following overhauls will be even more distributed. An early exchanged wheel again has a probability to reach either a longer or shorter life cycle and so do the late exchanged wheels. This requires the maintainer to adapt its work force to the required capacity and time schedule.

Additionally, a maintainer might not have the resources to overhaul a large amount of wheelsets in a short time period. Maintenance planning focuses on adapting original intervals to get the job done with available resources and could also mean outsourcing work to suppliers. (referring to London Underground maintenance strategy)

Coney and Yule provide reference values in their report about maintaining wheelsets of the Midland Mainline high speed train "MkIII" (UK) and state that one event of turning wheel flats (4 wheelsets) can result in up to 1000GBP in material cost. This was calculated taking into account that removing 1mm on the wheel radius could amount to 100 GBP.[95] It was further stated that a wheelset change is equivalent to around 4000 GBP material cost.[96] A comparison with Siemens Desiro UK mainland trains shows that their overhaul supplier charges 3042,83 GPB for a power wheelset overhaul excluding new wheels.

5.1.8 Summary

Predicting the wheel life cycle is a highly complex issue and the interviews within Siemens provided a large range of estimations. A more objective approach was chosen by implementing vehicle data, operational data and environmental data into a so called "parameter tool" in order to calculate a wear value and relate it to acquired reference wheel life cycles. This was done for all proposed concepts. Reference projects and their existing wheel life cycle mileages were used to predict the wheel life cycle for the new design concepts. The results vary but it is suggested that they represent a tendency of possible life. Predictions are stated to be between 1100k km and 1700k km. Further field data was gathered to create a bigger picture of actual LU wheel life cycles. Values range from 500k km (old rolling stock) to 1900k km (new trains). The wheel wear pattern was analysed and concluded that no flange wear is dominant on LU wheels. The Siemens design proposals include comparatively small wheels (diameter) and positive and negative aspects were discussed.

For the LCC models a mean value of wheel life was taken with 1500k km. This mean value was then tested for plausibility by including reprofiling intervals and the amount of material turned off from LU. It is suggested that even without flange wear the reprofiling events will be limited to three times over the life cycle.

For LCC calculations the prediction of the wheel life cycle is one of the most uncertain values and thus related to risk. It is suggested that either risk is economically included in the LCC calculation or a more detailed approach should be followed, which could be the simulation of wheel wear.

[95] (wheelset material cost divided by tread thickness (new – scrap size), excluding down time cost)
[96] Coney and Yule (2001, p. p.255)

5.2 Gearbox maintenance

The analysis of cost triggers showed that the gearbox overhaul is the most dominant cost factor for wheelset maintenance. Yet the discussed wheel exchange triggers the overhaul of gearboxes because they can only be overhauled during a wheelset overhaul. The reason for this is because overhauling the gearbox requires the wheels and axle bearings to be removed first. Furthermore, not only the gearbox overhaul creates costs as regular light maintenance is carried out as well, which includes oil changes, visual checks of the mounting and oil stand. Checking for damage and the clearance of the water drainage is included in light maintenance. A gearbox is considered to be as safety critical as axles and axle bearings because a failure could lock up the wheels and lead to a derailment of the train. Therefore maintenance actions are crucial.

The purpose of gearboxes is to transfer torque from the motor to the axle. Most electrical motors operate with higher speeds than the rotation of the wheelset and thus reduction gearboxes are installed in trains. For variant 1, Syntegra, the motor has to provide the required torque already produced at the angular speed dictated by the wheelset. In the other two concepts, different types of gearboxes are installed. One variant is a single stage gearbox design and the other one a two stage gearbox design. Both variants have a different amount of bearings and seals installed but are not fully designed yet due to the early project stage.

The supplier of the drive train has conducted an offer-study and provided values for maintenance intervals, material prices and man hours needed. This information was included in the original LCC models which will be discussed, evaluated and benchmarked.

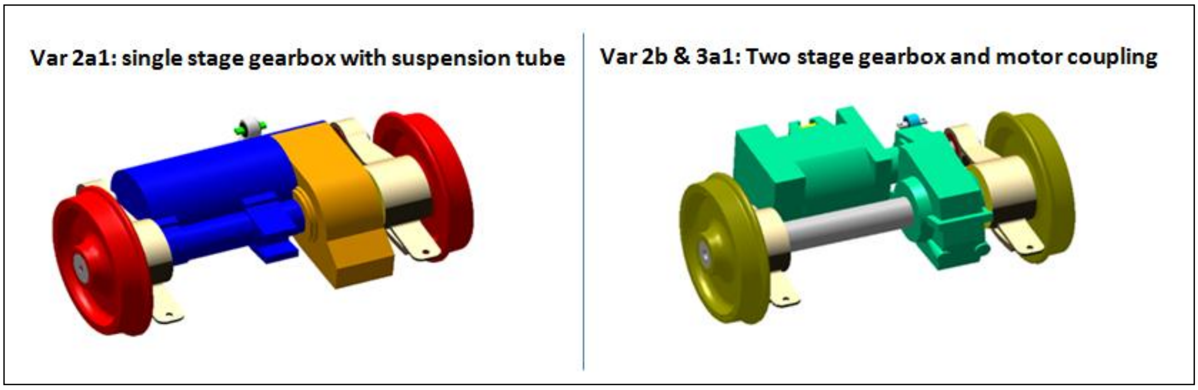


Figure 61: Gearbox design concepts

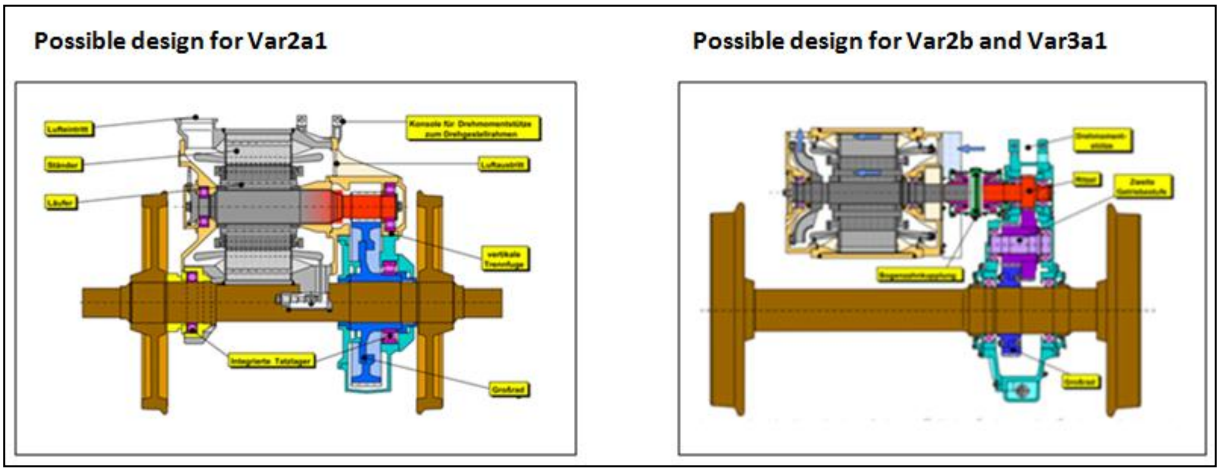


Figure 62: The life inside the gearbox types[97]

These two types of gearboxes are the main differentiator between concepts and shall be further discussed.

Single stage gearbox with suspension tube: This design does not require a clutch by using the output shaft of the motor as a pinion, which has a shared bearing in the gearbox. This is possible as the motor is mounted on the wheelset axle via suspension tube and no relative movements to the gearbox are created. For this mounting, two bearings are required on the tube to allow relative rotations. Additional maintenance efforts and thus costs are caused by these two bearings which require annual regreasing.

Two stage gearbox: This design requires a clutch but no suspension tube. As it is a two stage gearbox an intermediate shaft is required and thus additional bearings and gear wheels are installed. There are approximately 7 bearings built in, 2 on the main axle, 2 on the intermediate shaft and 3 on the pinion.

The maintenance of both gearboxes will be explained and the maintenance tasks will be divided into light maintenance and heavy maintenance.

5.2.1 Light gearbox maintenance

The light maintenance includes oil changes and visual inspections. Oils in gearboxes have to fulfil certain standards that are specified in DIN 51517 and DIN 51519. Required oil exchange intervals are set by mileage and time. The maintenance activity is executed once one of the limits is reached.

Initial oil change only has to be carried out once and the interval set is specified by the gearbox manufacturer. The purpose of it is for the removal of metal content caused by increased abrasion at the beginning of the life cycle. Existing intervals have been questioned and newly suggested mileages were approved by the gearbox manufacturer.

[97] Haigermoser (2002, p. p.177ff)

Variant	Initial situation	Updated situation
Syntegra	-	-
Single stage gearbox with susp. tube	15.000 km	10.000 km
Two stage gearbox	5.000 km	10.000 km

Table 22: Initial oil change intervals

Regular oil change has to be carried out in order to ensure complete lubrication of the bearings. Furthermore it is a good monitoring tool when including oil analysis from samples. Both gearbox variants had different oil change intervals which were questioned again and changed to 150.000 km for both of them. The gearbox manufacturer has approved the new values.

Variant	Initial situation	Updated situation
Syntegra	-	-
Single stage gearbox with susp. tube	400.000 km or 24 months	150.000 km or 24 months
Two stage gearbox	150.000 or 24 months	150.000 km or 24 months

Table 23: Regular oil change intervals

During operation the maintainer of trains often changes intervals because real life data and experience is then available. The contamination of the oil is an important indicator for the condition of the gearbox and an increased metal content in the oil indicates wear of metal parts in bearings (rollers and cages).

Siemens in Northampton, UK overlooks the maintenance of around 350 mainland trains and engineers have developed an advanced approach to oil changing[98]:

“Here we can reduce the amount of oil exchanges by taking samples of the oil. Knowing if there are any issues with the metal or zinc content in the oil enables us to only exchange oil once samples suggest doing it. This saves cost and gives us a tool to understand the current condition of our gearboxes.”

Visual checks: The gearbox mounting is safety critical because a failure of it would lead to the derailment of the train. This for example happened at LU Central line in 2003. Therefore the mounting is regularly checked. This check is economically beneficial when the train is in the depot and other checks are done at the same time and referred to as maintenance synchronicity.

Variant	Initial situation	Updated situation
Syntegra	-	-
Single stage gearbox with susp. tube	37.500 km	50.000 km
Two stage gearbox	37.500 km	50.000 km

Table 24: Visual checks of gearbox mounting

The changes presented are approved by the gearbox manufacturer and were also agreed on for the visual check of the motor. They can now be performed at the same time.

[98] Siemens Northampton, UK - 20.6.2013

5.2.2 Heavy gearbox maintenance

The gearbox overhaul is the main cost factor of maintenance costs over 40 years. Therefore it is one of the biggest decision criteria for choosing a concept. The wheels on the axles and the axle bearings have to be removed in order to access the gearbox and thus require all steps of a wheelset overhaul to be executed. The synchronicity of gearbox life and wheelset life which includes the wheel life cycle and bearing life cycle is necessary. An actual problem at London Underground makes this even clearer. Their wheelsets were supposed to be overhauled after 8 years but due to cracking of bearing cages in the gearbox the overhaul interval had to be set to 4 years. This doubles the amount of overhauls required and doubles the cost of maintenance. As a whole fleet is affected, a large financial impact is created.

In particular, when considering costs at the gearbox overhaul, it is important to keep two types of cost in mind. On the one hand, the material cost for parts to be exchanged and on the other side the amount of working time required for the overhaul. Cost from facilities, equipment and other resources like energy are not included as the utilised LCC models only consider material and personnel costs.

Overhaul of	Working time	Material price
Single stage gearbox	1800 min (30 h)	2069 €
Two stage gearbox	1440 min (24 h)	1792 € (= -15% supplier price)

Table 25: Material price of overhaul and man hours required

It was one of the derived research questions from chapter 5 to verify these values and prove their plausibility. The early design stage of the gearboxes and thus the lack of knowledge about parts built into the gearbox did not enable for a detailed cost analysis. Another approach was chosen where different types of gearboxes with related costs and working time requirements were benchmarked.

Gearbox overhaul benchmark

London Underground, supplier companies and gearbox manufacturer provided overhaul information which was then compared.

London Underground for example stated that a gearbox overhaul for a single stage gearbox on one of their lines costs around 3550GPB, where 1500GBP are material costs and 2000GBP is spent for the required work which is around 20 hours of manual labour.

Another reference was established by visiting the Siemens supplier LucchingRS in Manchester. A time study was conducted and gearbox overhaul steps structured and the required working hours related to the process steps, figure below.

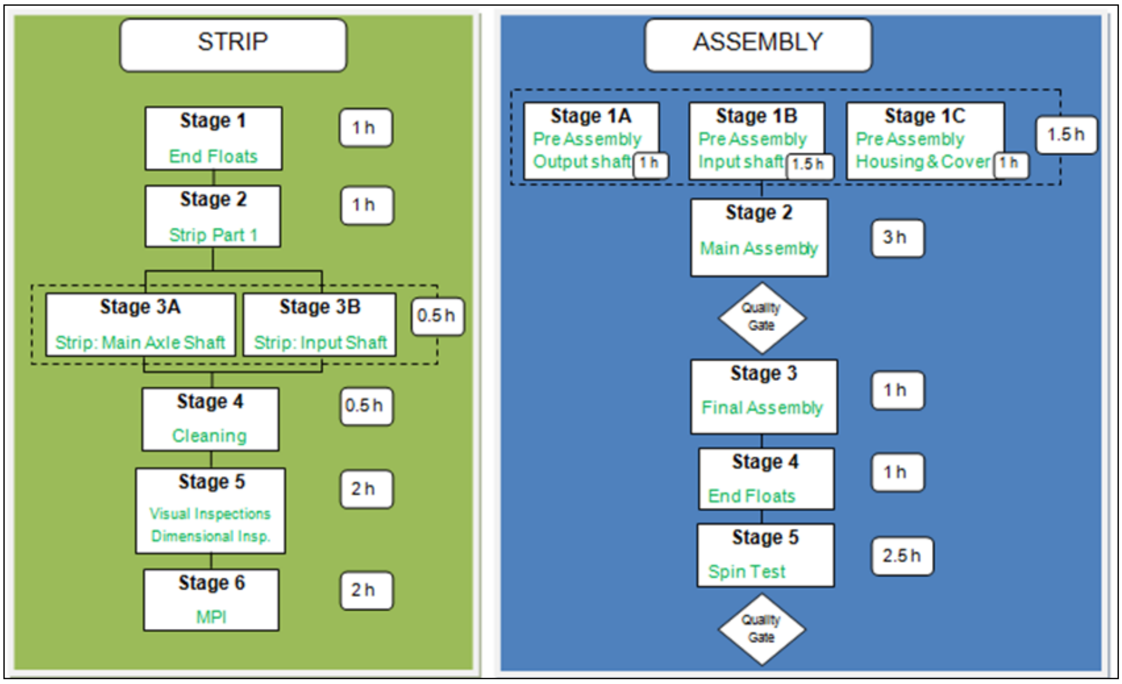


Figure 63: Strip and assembly process of a Desiro UK gearbox

The stripping process has a lead time of about 8 hours whereas the assembly process requires around 9 hours. Due to the fact that more than one person is working on a particular stage at a time, the man hours required are suggested to be 40 hours.[99]

This information and further sources were studied and included in an overview table. The table includes information regarding the type of gearbox, price or cost related quantity and when and where the information was received. Both proposed gearbox variants were then compared with cost and price values.

[99] Workshop at Lucchini RS – overhaul of Siemens Desiro UK gearboxes

Gearbox OVERHAUL Reference	Gearbox application	Type of gearbox	Quantitiy #	Required man hours	Cost	Price	EUR / gearbox GBP -> EUR (1,15)	Date of offer/ information	Data Reliability (+,++,+++)	Data gathered
London Underground	Central line trains of London Underground	1 stage Flender	~ 2000 #	20h	1500 GBP material 2000 GBP personal	-	4.025 (Cost)	14.06.2013 Workshop	+++	Workshop with LU in Leeds 14.6.2013 Statement of LU
Lucchini RS	Siemens Desiro UK trains	2 stage IG Watteeuw	long term contract with Siemens (10 years)	40h (interview)	-	4.047 GBP	4.654	22.08.2013 Contract	+++	Visiting Lucching RS, Manchester 26.6.2013 Values from contract
Eisenbeiss	Underground U4 Frankfurt	-	offer for 688 #	-	-	3.285 EUR offer 2.200 EUR material	3.285	11.02.2011 Offer	+++	Data received from Siemens Graz 1.5.2013
Gmeinder	Underground M1 Praha	2 stage Bombardier	offer for 1060 #	-	-	5.042 EUR	5.042	13.09.2013 MS excel	+++	Data received from Siemens Praha 5.8.2013
Bombardier	Underground M1 Praha	2 stage Bombardier	offer for 1060 #	-	-	5.990 EUR	5.990	13.09.2013 MS excel	+++	Data received from Siemens Praha 5.8.2013
Eisenbeiss	Underground M1 Praha	2 stage Bombardier	offer for 1060 #	-	-	4.610 EUR	4.610	13.09.2013 MS excel	+++	Data received from Siemens Praha 5.8.2013
Siemens, Praha	Underground M1 Praha	2 stage Bombardier	internal, 1060 #	15h	300 EUR personal (20 EUR/h)	1.790 EUR (material, (Gmeinder)	2.090	13.09.2013 MS excel	++	Data received from Siemens Praha 5.8.2013
Concept Var 2a	Suspention tube design	1 stage no completed design, IDT	feasibility study > 2000 #	30h estimated by IDT	1.500 EUR personal (50 EUR/h)	2.069 EUR material	3.569 (Cost)	01.04.2013	++	Data from Siemens IDT SA LCC 4/2013
Concept 2b & 3a1	Conventional desgin (motor mounted on frame)	2 stage no completed design, IDT	feasibility study > 2000 #	24h estimated by IDT	1.200 EUR personal (50 EUR/h)	2.108 EUR material	3.308 (Cost)	01.04.2013	++	Data from Siemens IDT SA LCC 4/2013 (-15% stated in LCC - is not confirmed by IDT)

Table 26: Data gathered for gearbox overhaul cost comparison

Overhaul costs and also overhaul prices were calculated and benchmarked. The benchmark includes prices as it was not possible to find out profit margins of received offers.

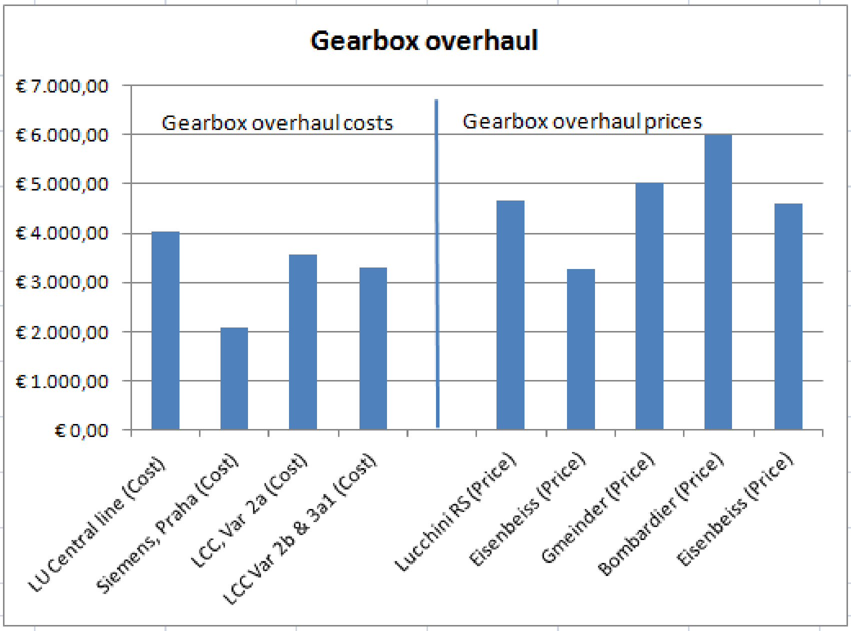


Figure 64: Gearbox overhaul cost/price benchmark

The benchmark shows that both gearbox design variants are in a competitive range compared to similar gearbox overhaul costs. Bombardier's offer for a single stage gearbox overhaul set the upper limit (5.990€) and the Siemens Praha cost study regarding the same gearbox gave the lower limit (2.090€) mainly due to the low personnel cost.

Optimisation potential of gearbox maintenance costs

A common interval for gearbox overhauls is mostly done between 8 to 10 years. A common question is to whether the gearbox overhaul could be done at the first wheelset overhaul or if it could be delayed to the second one. This strongly depends on the accumulated mileage until overhauls and also the elapsed time. One limiting factor for the overhaul period is the seal rubber parts which get brittle with time. The most critical parts for safety and for functionality are the gearbox bearings. They are the most strained components, needing constant lubrication and are historically the weakest link in gearboxes. Stretching the gearbox overhaul increases the risk of bearing failures but would save costs. The table below shows the cost impact of changing the gearbox overhaul (for a whole train and 40 years) to every 2nd wheelset overhaul.

Concept	Overhaul standard	Overhaul 20 years	Cost savings
2a1	1500k km	3000k km / 20 years	- 112 288 €
2b	1500k km	3000k km / 20 years	- 94 208 €
3a1	1200k km	2400k km / 16 years	- 94 208 €

Table 27: Cost savings related to a stretched gearbox overhaul

A saving of around 100.000€ per train is tempting. Hence, the feasibility of a reliable stretching of the interval shall be discussed. Experts were interviewed and their response is summarised as follows.

Expert interview with gearbox engineer from Siemens-Flender[100]:

“Nowadays designing a gearbox in a way that bearing lubrication is guaranteed at all time is not a big issue anymore. It can be fully simulated already in early design phases. But stretching the gearbox overhaul to 20 years is too much, a life time of 12, 13 years can be considered as achievable.”

Expert from Siemens maintaining Praha’s Underground[101]:

“At the first wheelset overhaul we took the gearbox and sent it off for condition assessment. The results showed a faultless gearbox which was why we decided to not overhaul them with the first wheelset overhaul and why we waited until the second overhaul. The first wheelset overhaul was done after 8 years which is around 800k km due to a yearly mileage of 100k km. This means we will overhaul our gearbox at the second overhaul that is planned after 16 years and a total mileage of 1600k km. At the moment we are considering to install vibration monitoring to stay aware of the condition of our gearboxes in service.”

London Underground trains run 150k km a year and the planned wheelset overhauls are already set to 10 years. This will not allow for the gearbox overhaul to be done at the time of the second wheelset overhaul only.

For the concept decision, the question is; which gearbox design is cheaper to maintain over 40 years? The comparison stated above showed that the single stage suspension tube gearbox is

[100] Siemens workshop, London - 16.4.2013
[101] Siemens Northampton, UK - 31.7.2013

more costly than the other variant. An interview with a gearbox specialist from ZF confirmed this study[102]:

“My personal statement and the ZF background is that the two stage gearbox has the tendency to be cheaper than the single stage suspension tube gearbox. Suspension tube bearings require re-lubrication every year which sums up over 40 years. The gearbox overhaul itself is commonly set to 8 years as this is a recommended interval for exchanging the rubber parts in it.”

Gearbox design related to the overhaul

It is commonly known that bearings are the weakest link in a gearbox. Bearings are calculated to last for a defined mechanical life (e.g. L10) if lubrication is ensured. Abrasion on the roller elements and more importantly the bearing cage are life-limiting factors. Furthermore, it makes a difference in how close the gearbox is designed to physical limits and the material strength. A simulation of the gearbox life on a test rig is not really possible because the life time cannot be simulated with an increased rotation of bearings. This would not represent operational conditions.

Another question is if bearings can be inspected without stripping the gearbox, which has to be answered with no, even though this would be advantageous. But the design can still influence the stripping process as it is dependent on the partial line of the gearbox housing. Commonly it is vertical or horizontal. A gearbox overhaul without stripping axle bearings and wheels could be achieved if the gearbox parting line was horizontal. Then the part of the gearbox on the wheelset axle could remain unchanged while the other elements could be changed. This would make the process more independent from the wheelset overhaul because the exchange of bearings would be possible without removing the gearbox from the axle. Intermediate and pinion to be exchanged, but bearings on the wheelset axle completed at the 2nd overhaul.

Material costs are design related and during a gearbox overhaul all bearings, seals and the oil is exchanged. Parts such as gear shafts and the gears itself are tested and measured but do not need to be changed most of the time.

Labour costs are calculated with the time needed for the overhaul work and is multiplied with an hourly wage of the qualified workers. A gearbox design that reduces the working time required will of course be beneficial. Overhead costs, such as warehouse costs, supporting resources etc. are not considered in theoretical life cycle cost models as too much information from a customer would be required.

5.2.3 Summary

Both gearboxes are in a competitive cost range which was shown in a benchmark. The decision for one of the wheelset and bogie designs will also be affected by the type of gearbox used. The variant 2a1 includes a suspension tube mounting to support the motor on the wheelset axle which is related to an annual maintenance process of the bearings. In contrast, Var.2b and

---

[102] Siemens Northampton, UK - 27.9.2013

Var.3a1 use a two stage gearbox that requires a coupling unit to the motor and has more bearings and seals installed. But due to the fact that no suspension tube is required these variants are still a bit cheaper to maintain and are acknowledged to be the cost winners. Still it has to be considered that the difference is not great and other aspects such as the length of the wheelbase related to the gearbox design might be more important.

5.3 Wheelset bearings

Wheelset bearings are one of the most critical parts on a train as they hold the wheelset axles and ensure their rotational movement. A failure of these bearings would most likely lead to the derailment of the train which is why frequency monitoring and heat detection measurements are in place on mainland and high speed railway tracks.

Wheelset axle bearings are normally either taper roller bearings or cylindrical roller bearings. At the moment London Underground only uses taper roller bearings. For the Siemens design concepts both variants are still an option.

Regreasing: The grease in a bearing and not the mechanical strength is the limiting factor for a bearing life cycle. Therefore regreasing of bearings is a standard maintenance procedure.

Overhaul: During a wheelset overhaul bearings are pressed off the axle and are investigated and optionally reused or simply renewed. This strategy has to be confirmed with the bearing manufacturer. The most popular producers are SKF, FAG and Timken.

5.4 Wheelset axles

Wheelset axles are one of the most safety critical components and have to withstand high dynamic loading. Axles are supported by axle bearings and wheels are pressed onto them. Axles are normally not exchanged during a whole train life but are regularly tested to make sure that no cracks have occurred in operation. Over a life cycle of 40 years maintenance of axles includes testing and inspecting. The testing methods and testing intervals utilised are the triggers for the costs. The OEM initially specifies testing requirements in maintenance manuals but in the end it is the operator’s responsibility to ensure a safe train operation.

The following testing methods have been established in the railway industry[103]:

- Ultrasonic testing (UT)
- Eddy current testing (ET)
- Magnetic particle Inspection (MPI)
- Visual testing (VT)

Ultrasonic testing is the proposed method in our LCC model and an interval of 400k km is suggested. But how are these intervals derived? There are three standard ways of defining the testing interval[104]:

[103] Cantini and Beretta (2011)
[104] Referring to Siemens experts in wheelset department, 05/2013

- Historically, based on past experience of rolling stock
- Theoretically with simulation models
- Physical tests on a rig

The problem here is that theoretical simulation methods are still particularly inaccurate compared with the results of physical testing. Historical data is often based on “incorrect” reasons for the testing interval.

London Underground has set its ultrasonic testing intervals to 4.5 years which is equivalent to around 675k km. But LU specifies that whenever wheels are removed from the axle, the axle itself has to be MPI tested. Removing wheels from the axle can create scratches on the journals and thus a certain scrap rate of axles is involved. LU referred to a value of around 3% scrapped axles due to wheel removal.

Axle Design: The proposed design concepts include hollow axles as this has become common due to the easy access for ultrasonic testing and also weight reduction. All existing trains at LU have solid axles which are produced with cold rolling and require fibre cloth wrappings.

The axles of concepts Var1 and Var2a are protected by the design of the wheelset. In Var1 the axle is fully covered by the motor housing and Var2a protects the axle due to the suspension tube.

5.5 Summary

The next table provides an overview of the LCC input parameters that were analysed. Results and changes made concerning the wheelset and the gearbox are stated.

Category wheelset	Nr.	Cost model values before	C.L. before	Derived questions	Information gathered and Results	Cost model values afterwards	C.L. after
Measurement of wheelset	1	Interval 50 tkm	3	What interval is used at LU?	A standard interval set by LU is 6 months	75.000 km is implemented	4
	2	Measurement-rail is available	2	Does LU have this device, what type of measuring is used?	Diameteres are only measured on the lathe Profile is checked 6 monthly with a metal gauge Only Victoria line has a measurement rail	no measurement rail available therefore more time needed for measurement	4
	3	30 sec. per wheelset	2	Is 30 sec. right?	none of the lines which should be upgraded have a measurement rail	1 min per wheelset implemented	3
Reprofiling	4	**Interval 300k km**	3	What reprofiling strategy is implemented at LU?	LU northern every 3 years, other 1.5 years this values were initially set as standard values Strategy implies using wheel to the wear limit, no pre-reprofiling	decided that 4x reprofiling is unlikely with LU strategy and small wheel (700 to 650 mm) 3x reprofiling for 1.500k km -> 375k km (2.5 years) implemented	4
	5	Tandem-wheelset lathe is available	2	Do LU depots have a tandem lathe ?	Mobile wheel lathes are in most depots available. Bakerloo line does not have a lathe.	Therefore lead time unchanged	5
	6	Lead time per wheelset 15 min	2	How long does it take at LU.	Value is about right for the reprofiling process itself, considering the whole work flow it takes around a day	Unchanged	2
Wheel exchange	7	**Interval of 1500k km** except var 3a1 (=1200k km) (~931.miles)	2	Deriving tendency of wheel life compared to reference projects	~1.8m km - Northern line (flex frame bogie, 770 wheel) ~1,4m km - Jubilee line ,~1,1m km - Central lline No flange wear dominant Parameter tool used for prediction	Is a value that can be reached with new stock at LU. It is suggested that tread thickness lasts only for 3x reprofiling	3
	8	Required time 120h	3	Is this a good value ?	Lead time for wheelset overhaul ~7 days at LU's REW overhaul center	Unchanged	3
	9	Material cost for a wheel is 990l	3	What price would apply for LU?	Lucchini price for LU is 700GBP and for Siemens Desiro trains is 722 GBP	Reference prices would result in 805 EUR -> 900 EUR implemented	4
Wheelset bearing	10	Exchange after 3000k km	3	Is it ok to heat wheel for assembly?	LU uses SKF taperroller bearings - no inbord bearings installed across fleet LU standards are established and impose the exchange after latest 12 years 3 Mkm Would be a new option which would have to be explained and verified	Exchange interval is set to be the second overhaul	3
	11	Overhaul/Relubrication 1500k km	4	what are reference projects	Northern line 12years without regreasing Old lines, regreasing after 3 years	Unchanged	4
	12	Price per part 700 EUR	4	Is this the right price?	Reference Lucchini - Siemens contract: new 330GBP, overhauled 155GBP but bearing is bigger as it is an inboard bearing	Unchanged	4
Wheelset axle	13	**Ultrasonic test 400k km**	3	what dirves it and what alternatives are available	LU 4.5 years standard No hollow axles are used! Wrapping in fibre glas cloth compulsory.	set to 3.3 years 500k km implemented	4
	14	Duration 30 MMH	4	Time ok?	is a value interviewed people agreed on	Unchanged	4
Overhaul	15	**Interval 1200k km / 8 years**	4	What is the LU standard?	LU Standard 9 years Northern line stretched to 12 bogie & wheelset normally done at the same time	different scenarios established in LCC models	4

Table 28: Improved wheelset input parameters for LCC model

The next table provides an overview of the LCC input parameters analysed concerning the gearbox maintenance.

	Category wheelset	Nr.	Cost model values before	C.L. before	Derived questions	Information gathered and Results	Cost model values afterwards	C.L. after
Applying for all concepts	Visual check of gearbox mounting, oil level, leakness	16	Interval 37.5k km	3	Why, Can it be changed ?	Siemens IDT approves 50 tkm after enquiry	50k km implemented	4
	Visual check of gearbox/motor for damages	17	Interval 150k km	3	Can it be stretched ?	Siemens IDT approves 150 tkm after enquiry	Unchanged	4
	Visual Check Motor	18	Interval 37.5k km	3	Can it be stretched, check synchronicity with gearbox	Siemens IDT approves 50 tkm after enquiry	50k km implemented	4
Concept 2a1	Revision	19	Interval 1500k km	3		easily up to 12, 13 years - 20 too high, stretching only with condition monitoring	Unchanged	4
	Initial oil change	20	one time after 15.000 km	2	Why is there a difference compared to concept 2b	Set to 10 tkm, approved	10k km implemented	4
	Oil exchange	21	Interval 400k km	2	Why is there a difference compared to concept 2b	Change to 150k km is approved by Siemens IDT	150k km implemented	4
	Material Costs for gearbox revision set	22	2.069 l	3	What are compareable material prices?	Reference values gathered from London Underground, Siemens Praha, Lucchini RS	Unchanged, references show plausibility	4
	Work time needed for revision of gearbox	23	1800 MM min = 30h	3	What are comparable times?	Reference values gathered from London Underground, Siemens Praha, Lucchini RS	Unchanged, gearbox desing not defined yet	4
	Lubrication of Tatzlager		150k km	3	How long does it take at LU.	interview with ZF showed that this is a standard interval for ZF as well	Unchanged	4
Concept 2b	Revision	24	Interval 1500k km	3		easily up to 12, 13 years - 20 too high, stretching only with condition monitoring		4
	Initial oil change	25	one time after 5.000 km	3	Why is there a difference compared to concept	Set to 10 tkm, approved	10k km implemented	4
	Oil exchange	26	Interval 150k km	3	Why is there a difference compared to concept	No change required, 150 approved by Siemens IDT	Unchanged	4
	Material Costs for gearbox revision set	27	1.792 l	3	Is this in a common range for gearboxes?	Reference values gathered from London Underground, Siemens Praha, Lucchini RS	Unchanged, references show plausibility	4
	Work time needed for revision of gearbox	28	1440 MM min = 24h	3	What are compareable times?	Reference values gathered from London Underground, Siemens Praha, Lucchini RS	Unchanged, gearbox desing not defined yet	4
Concept 3a1	Same as 2b but REVISION different	29	Revision 1200k km	3	not considered as the difference is caused by the current converter	Siemens Praha, maintaining M1, does gearbox overhaul at the second overhaul which is 16 years and a mileage of 1.6m km after assesment at first overhaul could be stretched to second (16 years) - condition monitoring	Unchanged	3

Table 29: Improved gearbox input parameters for the LCC model

All findings will be implemented in the LCC models and concepts benchmarked with each other. The findings have included LU's maintenance strategy; hence the cost benchmark in the next chapter will consider the potential customer's boundaries.

6 Benchmark

The previous chapters have shown the types of life cycle costing that currently exist and what input parameters are required. Data from London Underground, railway industry suppliers and reference projects have been gathered, analysed and implemented into the models. The biggest cost drivers were identified to be the wheel life cycle and the gearbox overhaul and thus have been analysed in more detail and included in the LCC model.

The cost model was initially built up as static and then expanded further to a dynamic method.

Changes implemented

Maintenance strategy: 1.500k km wheelset overhaul	**was**	**Is**	**LCC influence**
Measurement of wheels	50k km	75k km	Decrease
Time for wheelset measurement	30sec	2min	Increase
Reprofiling interval	300k km	375k km	Decrease
Material price for wheels	990 EUR	900 EUR	Decrease
Ultrasonic testing	400k km	500k km	Decrease
Initial gearbox oil change	5k km & 15k km	10k km	De/Increase
Regular gearbox oil change	400k km & 150k km	150k km	De/Increase
Visual check of gearbox & motor	37.5k km	50k km	Decrease
Bearings are changed every 2nd overhaul	2nd or 3rd	2nd	Increase

Table 30: Implemented changes in LCC model

6.1 Static LCC

For each concept, the results are calculated by taking into account the occurrence of intervals, personnel and material costs and the number of parts on a train. The time value of money is not included and thus concept design differences causing temporal difference in maintenance cost expenditure are not considered.

The next figure below shows the accumulation of preventative maintenance costs per wheelset, including the gearbox over 40 years and per 9 car train unit. Divided by 18, the resulting figure would give us costs per single wheelset.

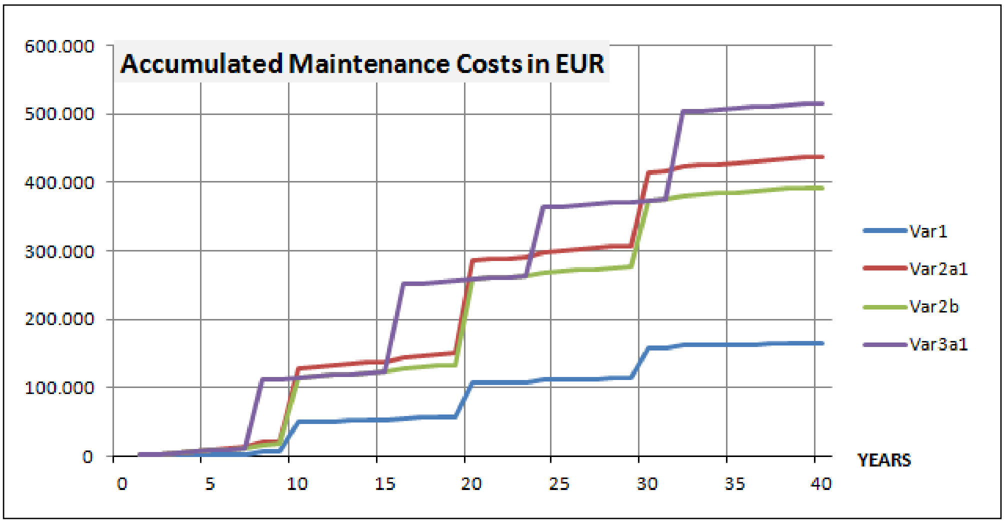


Figure 65: Accumulated maintenance costs as a step function

The accumulated costs are a type of step function with continuous costs over years due to light maintenance but the major expenditures from overhauls. Var1 is the most cost effective as the costs stay below 200.000€. Var2a1 and Var2b only include 3 overhauls but costs add up to around 400.000€. Var3a1 is the only design variant that requires 4 overhauls which makes it the most costly. This highlights that Var1 is the cheapest in terms of theoretical maintenance costs and this is due to the fact that there is no gearbox and less bearings are installed in the wheelset.

6.2 Dynamic LCC

Here the time value of money is included by using the net present value method (NPV) described in chapter 4 including a discount rate over years. The basis for the NPV is the year of investment, which is therefore year 0 of the train life cycle. The static cost values for each concept design over a period of 40 years can be seen in the bar chart below. They are accumulated considering the discount factor of the respective year.

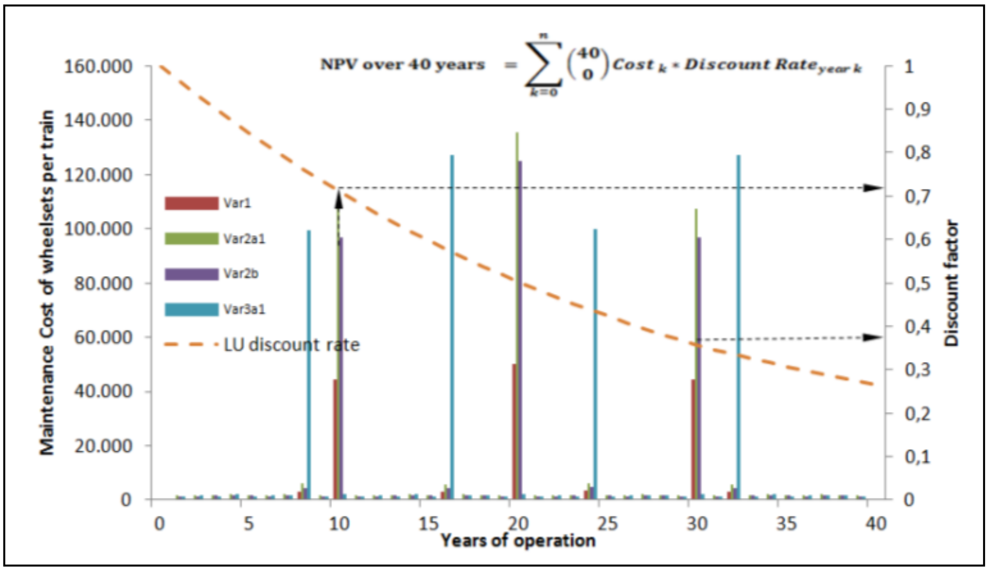


Figure 66: Dynamic LCC calculation of the four design variants

The discount value of LU is shown in context with annual expenditure and it can be recognised that expenses near the end of the life cycle do not have the full impact. Costs occurring in year 30 are only taken into account with a share of 36% of their sum because capital itself has earned interest over 30 years, which makes the expenditures appear less costly. Hence, the gained interest covers the remaining 64% of costs. The dominating influence of the discount rate over 40 years is remarkable and has to be investigated in more detail.

6.2.1 Influence of discount rates

Defining a discount rate for the cost models is crucial due to its impact. Referring to London Underground's business case development manual of 2009 the discount rate is set to 3.5% for costs in the first 30 years and lowered to 3.0% for the following years. Discount rates depend on the financial market and forecasts are subject to risk.[105]

Year	**Discount Rate**	Year	**Discount Rate**	Year	**Discount Rate**	Year	**Discount Rate**
1	**0,9662**	11	**0,6849**	21	**0,4856**	31	**0,3459**
2	**0,9335**	12	**0,6618**	22	**0,4692**	32	**0,3358**
3	**0,9019**	13	**0,6394**	23	**0,4533**	33	**0,3260**
4	**0,8714**	14	**0,6178**	24	**0,4380**	34	**0,3165**
5	**0,8420**	15	**0,5969**	25	**0,4231**	35	**0,3073**
6	**0,8135**	16	**0,5767**	26	**0,4088**	36	**0,2984**
7	**0,7860**	17	**0,5572**	27	**0,3950**	37	**0,2897**
8	**0,7594**	18	**0,5384**	28	**0,3817**	38	**0,2812**
9	**0,7337**	19	**0,5202**	29	**0,3687**	39	**0,2731**
10	**0,7089**	20	**0,5026**	30	**0,3563**	40	**0,2651**

Table 31: Discount rates for particular years

As maintenance costs are multiplied with the discount rate to derive the NPV in year 0, it is important to consider the time at which money is spent. The table above highlights that maintenance costs in year one would nearly have the full impact while costs that will be spent in year 39 do not account to their full amount. A logical procedure is to do maintenance as late as is safely possible.

A sensitivity analysis was performed to understand the full impact of the discount rate. LCC models were run with different discount rates and results are presented in the next figure.

[105] Transport for London (2009)

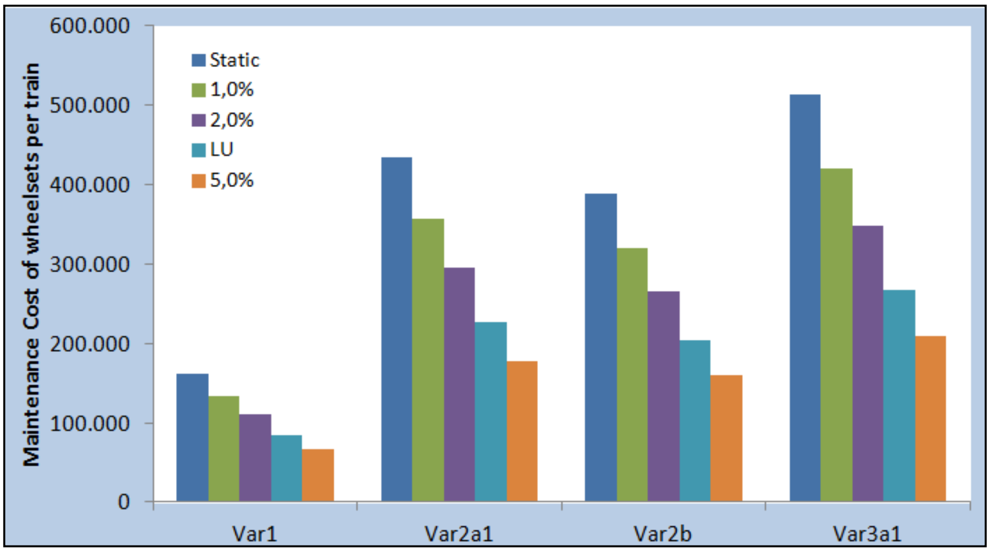


Figure 67: Results of static and dynamic cost accumulation

The results show that the total maintenance costs of bogie design concepts are reduced to about half the amount when using a 5% discount rate. The logical conclusion is that LCC models run with different discount rates cannot be compared and that the cost difference by the actual maintenance work required can be eliminated.

It was questioned if the discount rate could change the cost ranking as the influence of the discount rate is not linear over the years and benchmarked concepts are related to expenditures at different times. The next figure shows the transition point where the influence of the interest rate becomes so dominant that the original cost ranking is changed.

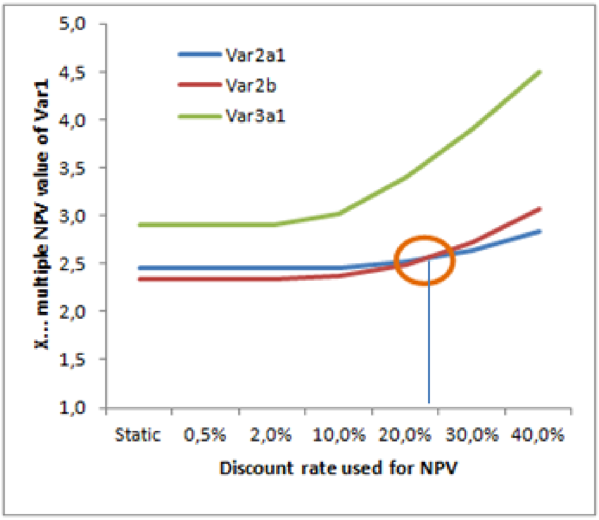


Figure 68: Influence of discount rates on variant ranking

The total amount of costs of Var1 was taken as a unit and the other design variants displayed as multiples of it. Executing a sensitivity analysis where costs were kept constant and the discount rate changed showed that for the first 10%, the differences, very nearly remain constant. Looking at the area above 10% discount rate the influence becomes dominant. The high interest rate favours concepts where the least amount of money is spent in the early life cycle. The transition point where the ranking of concepts is changed was calculated to be at a value of 24%. This is far too high to be relevant for train LCC models and the value not near to LU's discount rate.

6.3 Overhaul scenarios

As a further sensitivity anaylsis various overhaul scenarios were created to observe how total costs change when altering input parameters. The table below points out key input values and related maintenance intervals that had to be adjusted for synchronicity of tasks.

Overhaul		Axle	Wheel			Bearing		Gearbox
Bogie overhaul	Wheelset overhaul	NDT	Repfrofiling	Measurement	Exchange	Exchange	Lubrication	Overhaul
8 years	8 years	600 tkm	400 tkm	75 tkm	1200 tkm	2400 tkm	1200 tkm	1200 tkm
9 years	9 years	675 tkm	450 tkm	75 tkm	1350 tkm	2700 tkm	1350 tkm	1350 tkm
8 years	10 years	500 tkm	375 tkm	75 tkm	1200 tkm	3000 tkm	1500 tkm	1500 tkm
10 years	10 years	500 tkm	375 tkm	75 tkm	1500 tkm	3000 tkm	1500 tkm	1500 tkm

Table 32: Key input parameters according to maintenance strategy

Models run with these key parameters deliver the following results:

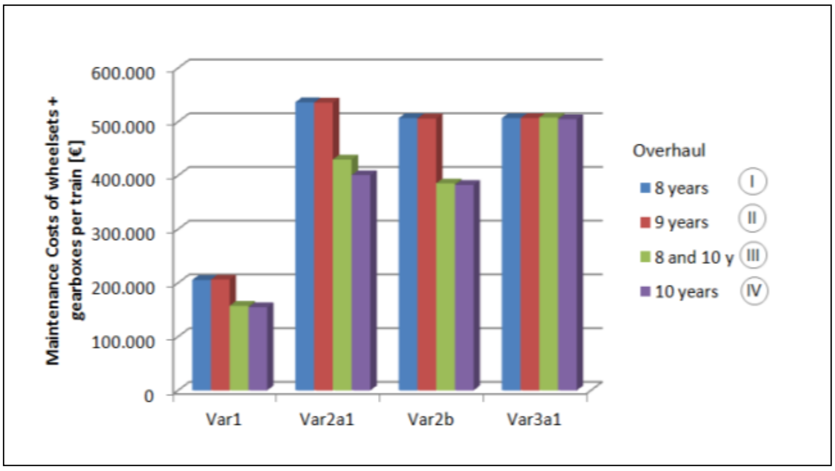


Figure 69: Costs caused by different maintenance strategies

The outcome strongly depends on the overhaul interval. Scenarios (I;II;IV) are examples for a combined bogie and wheelset overhaul, whereas (III) is a scenario with the bogie overhaul every 8 years and the wheelset overhaul every 10 years. Overhaul periods of 8 or 9 years require 4 repetitions over 40 years whereas an overhaul every 10 years only requires three executions. This shows that there is no benefit in terms of cost to change an 8 year overhaul period to a 9 year one. Only an increase from 8 to 10 years makes a considerable difference.

It was assumed that wheels in Var 3a1 cannot reach a ten year overhaul interval due to the grouped motor control and costs staying at the same level.

6.4 Benchmark results of initial and modified LCC analyses

The initial Siemens LCC models presented in chapter 5 were discussed and assumptions were analysed and questioned. Updated results were presented after established research on the wheel life cycle, gearbox maintenance and field data from LU was gathered. The differences in results shall now be presented using the static LCC models.

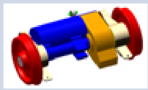
Total accumulated maintenance cost over 40 years and per 9 car train		Wheelset + Gearbox		Wheelset + gearbox + motor	
		before	actual	before	actual
Var 1		174.022 € 12%	164.73 € 11%	377.331 € 26 %	364.973 € 25 %
Var 2b		416.688 € 26 %	436.970 € 27 %	527.722 € 33 %	544.932 € 34 %
Var 2a1		404.900 € 25 %	392.551€ 25 %	515.029 € 32 %	499.608 € 31 %
Var 3a1		503.133 € 30 %	516.135 € 31 %	631.882 € 38 %	644.884 € 39 %

Table 33: Maintenance costs of concepts, before and after analysis

The table above shows the total amount of accumulated maintenance cost for all wheelset assemblies in the 9 car train unit. Calculations considering only the wheelset and gearbox were made and then extended by including the motors and couplings. Total maintenance costs for all bogies were used to calculate the percentage to which the wheelset assembly maintenance accounts for.

The LCC models are theoretical which means that no overhead costs, equipment costs, preparation time etc. is included. Comparing these values to experiences in the operational environment is difficult and a factor between 2 and 3 is suggested to be considered. Cassidy states that wheelset maintenance cost accounts for around 30% of the overall vehicle maintenance costs. Cassidy goes on to say that most of the cost can be attributed to re-profiling wheels.[106]

This general statement shows that wheelset maintenance costs are even more important than theoretical maintenance cost calculations suggest. They seem to account for a higher cost share when considering the costs of a train operator.

Initial LCC models and the updated LCC models will be compared in order to gain a better understanding about the influence of the train operator's environment. Cost increasing and cost decreasing findings were implemented into the LCC models as shown at the beginning of this

[106] Cassidy (2001, p. 289)

chapter. Both the benchmark of wheelsets (including the gearbox) and the whole drive assembly were established.

Maintenance cost benchmark including wheelset and gearbox

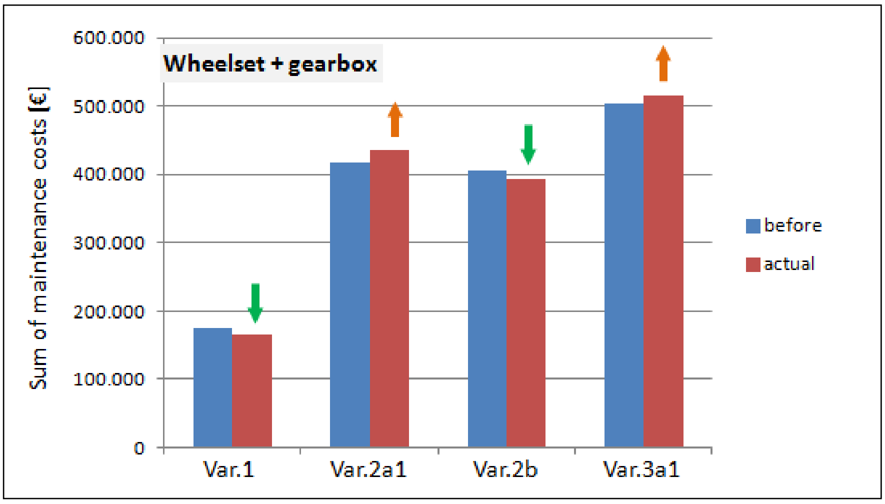


Figure 70: Total cost changes due to updated LCC model (wheelset + gearbox)

Implemented changes led to a change in costs and have also slightly influenced the cost difference between concepts. Yet changes are not significant and support the initial ranking of design concepts. The clear winner is still Variant 1, the Syntegra wheelset. This can be explained due to the fact that no gearbox is installed and no axle bearings are in the cost calculation. Axle bearings are simultaneously the motor bearings and related costs are accounted to the motor assembly. It is suggested that this type of design inherits the lowest cost but that only considering the wheelset without the motor would fall short. Thus, the benchmark was extended by including the whole drive train. Updated results can be seen in the following figure.

Maintenance cost benchmark adding the whole drive train to the wheelset

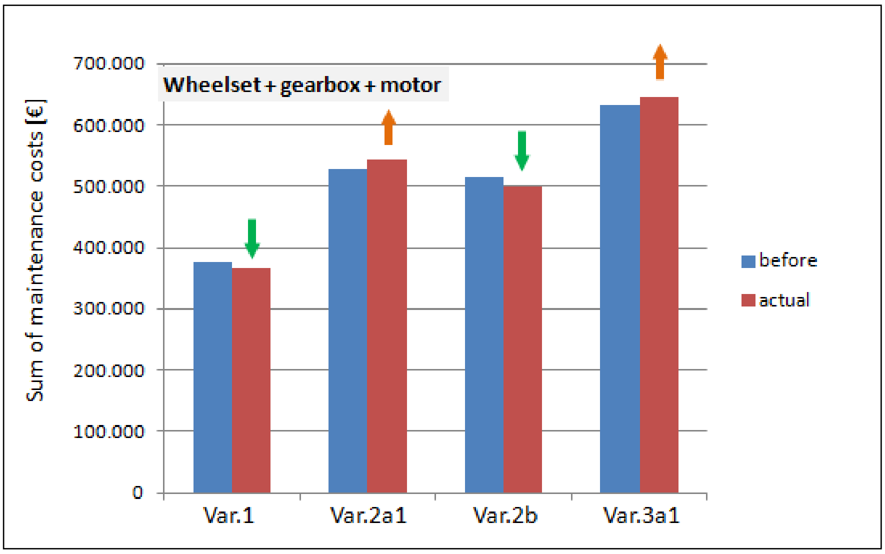


Figure 71: Total cost changes due to updated LCC model (wheelset + gearbox + motor)

Variant 1 remains the cost winner but not by as clear a margin as before. The motor of Var1 is more expensive and as soon as the motor has to be accessed the wheelset needs to be temporarily removed from the bogie. Variant 1 is also the newest design, as it was an innovation a few years ago and it might be hard to prove its reliability based on historical data.

It is suggested that all other variants are common concepts and the London Underground has extensive experience in maintaining this type of drive train design.

6.4.1 Indirect aspects of maintenance costs

Up to this point in time only material costs and personnel costs due to “net working time” were considered and no other issues included. Yet maintaining a wheelset includes transporting it, having spare parts in stock, being able to respond to failures, staff training and so on. Discussing issues related to the wheelset design will help to decide on a concept.

Capital lock up: LU as owner and operator of rolling stock will be influenced by the capital lock up that comes with spare parts. This would mean that Var1 is the most costly because the motor cannot be separated from the wheelset. This increases the money that is locked up as wheelset stock. This depends on the purchasing price of wheelsets and their drive train. Stock values for the Central line have shown that around 80 wheelsets are in stock to cover its fleet of 63 trains. For Var1 this would mean storing 80 motors compared to only a few with the other variants. Still, Var2a1 has a suspension tube which allows the un-coupling of motors but requires some work and adjusting to do so. Var3a1 on the other hand will be the design concept where the biggest stock has to be held because wheel diameters have to be matched within a smaller tolerance. The motors in this variant can be stored independently and do not need to match the wheelset stock size.

Weight of parts: The transportation of the wheelset and the transportation equipment needed depends on the weight of the assembly. The wheelset of Variant 1 again is the heaviest because the motor cannot be disconnected from the wheelset, followed by Var2a1 due to the suspension tube. This is only important for the wheelset overhaul; the bogie weights overall are quite similar to the lightest, being Var1.

Motor repair and overhaul: Motor overhauls and repairs can normally be completed without considering the wheelset or removing it. Taking Syntegra variant into account, it should be mentioned that the wheelset has to be removed from the bogie and the wheels removed if the motor is to be worked on.

The motor housing of Var 1 is the most exposed and the amount of damage allowed has to be considered. A high number of sparks caused by vertical deviations of the track and thus interrupted contact of the electricity shoe can damage the motor housing.

Axle repair and overhaul: Corrosion and protection of the wheelset axle is often an issue. Var 1 protects the axle from outside influences as it is within the motor housing. Var 2a1 does this as well due to the suspension tube. The exchange of wheelset axles in Var 1 would be very expensive due to the rotor of the motor mounted on it.

Wheelset	Var1	Var2a1	Var2b	Var3a1
Capital lock up	-	+	++	+
Weight	-	+	++	++
Motor repair	-	+	++	++
Axle price	-	+	+	+
Axle protection	++	++	-	-

Table 34: Indirect maintenance costs

6.5 Summary

Static and dynamic LCC results were compared and it was apparent that Variant1, the Syntegra concept, is by far the most cost effective concept. This is due to the direct drive system and the reduced number of parts to maintain. The second most cost effective concept is Variant 2b, which possesses the fully frame-mounted motor and the two stage gearbox. The cost difference in comparison to Variant 2a1, with the suspension tube concept, is not great.

However, deciding which bogie concept is the best will not necessarily be down to the wheelset assembly as lower costs of wheelset maintenance might be achieved at the price of higher cost somewhere else.

A sensitivity analysis implementing the dynamic LCC method (NPV) showed that the discount rate has a large influence on total costs. The customer needs to specify this discount value to allow a fair comparison of bidders. The analysis showed that the influence of the discount rate can cause a change to the cost ranking and was calculated to be 24% for this transition. Common factors are in a range of up to 10% and thus this is no longer relevant for the concept decision.

7 Conclusion

The maintenance of wheelsets is safety critical and is a major part of ensuring safe train operation. Nevertheless, a train operator wants to purchase train concepts that have low maintenance costs and still easily comply with safety standards. In connection with field data from the London Underground, the aim of this thesis was to compare 4 different metro bogie design concepts and to identify the most cost effective wheelset design over a period of 40 years.

Norms and standards are the basis for maintenance requirements. It was found that London Underground, as a government-run body, defines its own maintenance requirements. For the purpose of this thesis, these requirements were enquired into and received. A comparison with the British railway standards shows little divergence.

Deriving the bill of material for the 4 investigated design concepts enabled maintenance requirements for each part in the assembly to be considered and for initial maintenance plans over a defined period of 40 years to be created. Most of the parts do not remain in functional condition over this long period and a limited life-cycle requires exchange and maintenance intervals to be predicted. This means that maintenance plans include estimations about wear and aging of parts, which leads to preventive maintenance intervals. Intervals are essential for costs and an iterative improvement process for these key values was chosen. After initially using plans based on common industry values, subsequently these were improved by gathering field data and maintenance knowledge from experts in Austria and the UK.

Maintenance can be executed in different forms and the maintenance strategy and point of view is essential. Maintenance strategies can either take a run-to-failure approach, which is the most expensive approach and is also inappropriate for most train parts. An alternative is preventative maintenance, which seeks to reduce costs by taking measures before parts fail and to lengthen life cycles. A more advanced approach in maintenance is the so-called predictive and proactive strategy. Both strategies can only be implemented effectively once a system is in operation. In the early concept stage, the OEM’s point of view has to be taken into account, which means suggesting a preventive maintenance strategy.

Various methods were compared in order to relate the created preventative maintenance plans to costs. The key elements for the cost models were identified as material and personnel costs. The most appropriate methods were found to be life cycle costing techniques. A comparison between static and dynamic costing was made and concluded that both are sufficient for benchmarking concept variants. The static approach simply compares the sum of all occurring expenses while the dynamic one also includes the time value of money. The study of the London Underground business development manual supports using a net present value calculation, which is a dynamic costing method.

Net present value calculations include discounting all occurring costs to year 0 of the train life cycle. Hence, it represents the initial amount of money that is required to cover expenditures in the future. The main influence for this calculation is the discount rate, which depends on the interest rate that can be earned on the free market. Further studying of the London

Underground business development manual showed that a 3.5% discount rate for costs over the first 30 years is used and then a rate of 3% is used for the following years due to increased financial risk.

In an initial sensitivity analysis of static cost models it was found that gearbox maintenance and the exchange of wheels are the biggest cost factors. The wheel exchange accounts for around 30% of the total wheelset maintenance costs and the gearbox maintenance for around 35%. Consequently, these two cost types were focused on in more detail. Still, the other maintenance activities were not neglected but used for deriving questions for field data gathering.

It was necessary to gain as much information about the current London Underground maintenance strategy as possible in order to create models close to the customer’s specific boundaries. Contact with London Underground was established and information collected from various visits to depots and interviews with engineers.

London Underground has set up its maintenance regimes in service days and has 7 defined maintenance levels in place. A historical overhaul interval of 9 years is still in place but is constantly subject to optimisation programs. Lathes are installed at every depot (except Bakerloo and Piccadilly depots) and a shared overhaul facility (REW) is responsible for the heavy maintenance of bogies, wheelsets and motors. Further data was presented in overview tables and included in life cycle cost models.

The wheel exchange interval and reprofiling strategies were investigated during every visit. Achieved wheel life cycles vary strongly and are stated to be between 500k km (old trains) and 1900k km (new trains). Estimating a potential wheel life for the compared bogie designs turned out to be difficult. An initial approach was to interview railway experts asking for their opinion. Results showed a great variation between 400k km and 1600k km. Due to the range of statements, a more objective parameter tool was then used. This quantitative approach allowed wheel wear values for the new concepts to be calculated and reference underground projects that already provided real life data could be compared. The outcome was a potential life cycle ranging between 1100k km and 1700k km. The analysis of wheel wear pattern at LU showed that no dominant flange wear is recognised, which led to the conclusion that a 1500k km wheel exchanging period could be a feasible input parameter for the cost models.

It was recognised that the wheelset designs are built with smaller wheels, which has advantages and disadvantages. A smaller wheel tread thickness results in less re-profiling potential, which could mean a shorter wheel life but is related to lower energy costs, less track damage and reduced wheel wear. The simulation of reprofiling events showed that 3 reprofiling events are likely, which was used as another input parameter for the cost models.

Further, gearbox maintenance was implemented and an overhaul cost benchmark between concepts and reference projects established. The two stage gearbox turned out to be less costly but only by a marginal difference.

Updated cost models finally allowed a benchmark of the design concepts and showed that the maintenance costs of wheelsets on a 9 car train unit are as follows:

Maintenance cost benchmark:	Var1	Var2a	Var2b	Var3a1
Wheelset + gearbox	164.022 €	463.970 €	392.551 €	516.135 €
Wheelset + gearbox + motor	364.973 €	544.932 €	499.608 €	644.884 €

Table 35: Maintenance cost benchmark

The total accumulated cost demonstrated in the table above is dominantly influenced by overhauls, which include exchanging and reconditioning parts. A sensitivity analysis showed that stretching a standard overhaul period of 8 years to 10 years is beneficial and would reduce costs by around 20%.

The same benchmark was extended using the dynamic NPV method. A sensitivity analysis of the discount factor showed that a discount rate higher than 24% changes the cost ranking of the compared concepts. This value is too high to be relevant for the upcoming bid and the effect could be neglected.

LCC models are used in bid appraisals and stated component life cycles are commonly related to warranty agreements. This creates risk for the OEM because a certain degree of uncertainty of predictions cannot be avoided. Overly optimistic statements can create financial risk regarding possible claims in the future, whereas overly conservative values could present a disadvantage in terms of being awarded the contract. Therefore, it is important to discuss the evaluation criteria of life cycle costs with the customer and define boundaries for which these statements are valid.

On a component or assembly level, it is common to create LCC models that only include so-called net maintenance costs, which are predictions that are made by the OEM. Net maintenance costs do not represent occurring maintenance costs of the train maintainer but are a useful tool for demonstrating the maintainability of a particular design. Life cycle costs in the train operating environment include lots more factors such as overhead costs, equipment deprivation, preparation time for work etc. and cannot be included without this information from the a customer. Still, it was determined that comparing maintenance costs of design variants is a powerful tool for a variant decision.

It was found that maintenance costs of wheelsets are valid decision criteria for bogie concepts because wheelset maintenance accounts for around 30% of net bogie maintenance costs. References about these costs from the train operating environment, including all costs, even suggest that the wheelset maintenance accounts for 30% of the entire train maintenance.

This thesis was a first step in improving LCC models and making statements more reliable by including specific boundaries. A fair amount of data was collected and maintaining an open approach with potential customers during bid processes is recommended.

The final outcome of this work shows that the “Syntegra” wheelset Var.1 is the most cost effective in terms of net maintenance costs related to the wheelset. The wheelset includes the axles, the axle bearings and wheels. The advantage of the Syntegra is that no gearbox is installed and that the axle bearings are simultaneously the bearings of the motor. An extended benchmark including these motors showed that the great LCC advantage of Var.1 is reduced but remains great. Still, this design concept is very new to potential customers and the example London Underground showed that existing maintenance processes would have to be changed and a learning curve accepted. Visits to LU also showed that they keep around 3% spare wheelsets in stock because wheel diameters under a train have to be matched. With the Syntegra concept the wheelset assembly cannot be separated from the motor which would increase the capital that is locked up. This is a disadvantage but due to the independent wheelset control the required amount of wheelsets in stock would be smaller. The Syntegra also has the biggest potential for a long wheel life due to its short wheelbase and flexible wheelset guidance, which would be beneficial on a curved track like those of LU.

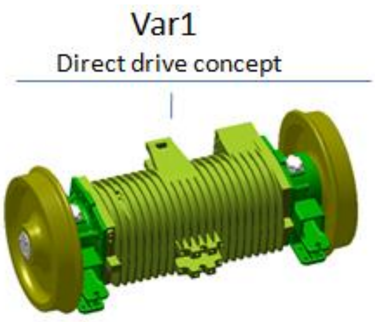


Figure 72: Lowest wheelset maintenance costs: Var1, the direct drive concept

The second most cost effective design is variant 2b, which is the design with the two stage gearbox. There is not much difference between second and third place (Var.2a) and both variants are considered as suitable for the London Underground because there is extensive experience of these wheelset types. As there is little difference in maintenance costs, the technical aspects of both wheelsets might be more suitable for the ranking.

The suspension tube concept (Var2a1) has a 0,2m shorter wheelbase compared to Var2b which is possible due to the reduced distance between gearbox and motor but also because of the traction link that can be mounted on the gearbox. A shorter wheel base is an advantage for curvy tracks and can lead to a longer wheel life cycle. Another advantage for the suspension tube concept is that the axle is automatically protected against electric spars and stone chipping by the design.

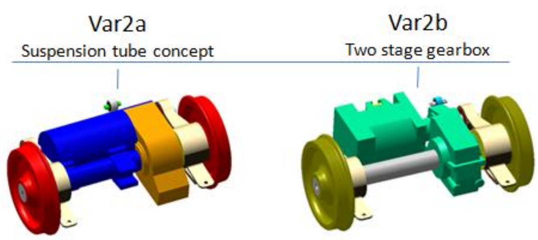


Figure 73: 2nd and 3rd place

In the future, potential customers will have a choice between these wheelset concepts. A refinement of LCC analysis can only be carried out once customer requirements and boundaries are specified. This analysis has taken into account the train operating environment of London Underground and it was concluded that all new wheelset concepts would be suitable.

8 List of references

ATOC. (2013). Train Companies Retrieved 10.07.2013, from http://www.atoc.org/train-companies/

Batchelor, J. R. (1997). *The LUL safety case - a train maintainer's view*. Paper presented at the Third International Conference on - Train Maintenance Tomorrow ... and Beyond.

Bevan, A., Molyneux-Berry, P., Mills, S., Rhodes, A., & Ling, D. (2013). Optimisation of wheelset maintenance using whole-system cost modelling. *Journal of Rail and Rapid Transit, Part F*. doi: 10.1177/0954409713484712

British Standard. (2010). Railway applications *The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS)* (Vol. BS EN 50126:1999): BSI.

Cantini, S., & Beretta, S. (2011). *Structural reliability assessment of railway axles*: Lucchini RS.

Cassidy, P. D. (2001). *A new wheel material for the new century*. Paper presented at the Railtex - International Railway Engineering Conference, Birmingham.

Coney, M., & Yule, N. (2001). *Retro fitting a modern WSP to Midland Mailaine HST coaches*. Paper presented at the Railtex - International Railway Engineering Conference, Birmingham.

Dale, S. J. (1993). *Life Cycle Costing for Construction*. Glasgow: Blackie Academic & Professional.

Day, M., & Scappaticci, M. (2001). *Total cleanliness control approach to condition monitoring of railway fluid systems*. Paper presented at the Railtex - International Railway Engineering Conference, Birmingham.

Department for Transport. (2012). Railways (Interoperability) Regulations 2011 *Roles, Responsibilities and Interactions* (Vol. RIR2011): Department of Transport.

Elliot, R. (2001). *Maintenance plans for new vehicles*. Paper presented at the Railtex - International Railway Engineering Conference, Birmingham.

Etwell, M. (2001). *Optimizating Maintenance*. Paper presented at the Railtex - International Railway Engineering Conference, Birmingham.

European Committee for Standardisation (CEN). (2010). Railway applications *In-service wheelset opteration requirements* (Vol. EN 15313).

Flanagan, R., Norman, G., Meadows, J., & Robinson, G. (1989). *Life Cycle Costing: Theory and Practice*: BSP Professional Books.

Gibbs, R. E. (1998). *Life-cycle cost modelling of military aero-engines in Rolls-Royce*. Paper presented at the Seminar for Life Cycle Costs.

Haigermoser, A. (2002). *Schienenfahrzeuge*. Vorlesungsskriptum. Graz University of Technology.

Holmes, C., & Dymott, M. P. (1997). *Maintaining standards in a changing world - London Underground's approach*. Paper presented at the Third International Conference on - Train Maintenance Tomorrow ... and Beyond

IEC - International Electrotechnical Commision. (2004). Dependability management *Application Guide - Life cycle costing* (Vol. IEC 60300).

Innotrack. (2006). Guidline for LCC and RAMS Analysis: Innotrack.

Jun, H. K., & Kim, J. H. (2007). *Life Cycle Cost Modeling for Railway Vehicle*. Paper presented at the ICEMS, Seoul, Korea.

Kämpfer, B. (2005). *Modell des Verschleißverhaltens von Schienenfahrzeugrädern.* Doktorat, TU Graz, Graz.

Levitt, J. (2003). *Complete Guide to Preventive and Predictive Maintenance* (1st ed.). New York: Industrial Press Inc.

London Underground Ltd. (2003). Rolling stock wheelset profiles (Vol. E 6347 A3). London.

London Underground Ltd. (2006). Engineering of rolling stock wheelsets (Vol. E 6340 A3).

London Underground Ltd. (2010). Overhaul of Wheelsets *Part 3: Overhaul Activities* (Vol. EO.14.06.01). London.

London Underground Ltd. (2013). UK-London: Rolling stock. Retrieved from Ted website: http://ted.europa.eu/udl?uri=TED:NOTICE:115076-2013:TEXT:EN:HTML

Martinsen, W. O., Rahn, T., Hermann, H., & Hochbruck, H. (1997). *ICE. Zug der Zukunft*. Darmstadt: Hestra.

McEwan, J. J. (2000). *Tread profile monitoring and maintenance*. Paper presented at the Wheels and axles - Cost effective Engineering, London.

Mitchell, J. R. (1998). *The application of life cycle costing techniques to the British Aerospace RMPA proposal*. Paper presented at the Seminar for Life Cycle Costs.

Mobley, R. K. (2002). *An Introduction to Predicitive Maintenance* (2nd ed.). Oxford: Elsevier.

Morbey, C. A. (2001). *Adtranz DMUs - delivering the future*. Paper presented at the Railtex - International Railway Engineering Conference, Birmingham.

Morris, F. J. (1997). *Moving maintenance into the next generation*. Paper presented at the Third International Conference on - Train Maintenance Tomorrow ... and Beyond.

Office of Rail Regulation. (2012). Rolling stock Retrieved 16.07.2013, from http://www.rail-reg.gov.uk/server/show/nav.123

Office of Rail Regulation. (2013). *Starting mainline rail operations - A guide to the regulatory framework*. London: Retrieved from http://www.rail-reg.gov.uk/server/show/nav.1834.

Rail Safety and Standards Board. (2008). Cost effective turning of flange worn wheel profiles. London: RSSB.

Rail Safety and Standards Board. (2012). Rail Vehicle Maintenance (Vol. GM/RT2004). London: RSSB.

RSSB. (2013). RGSonline. Retrieved 20.08.2013, from RSSB

Siemens. (2013). Siemens Rail Retrieved 28.11.2013, from www.siemens.com

Strunz, M. (2012). Instandhaltung *Grundlagen - Stategien - Werkstätten* doi:10.1007/978-3-642-27389-6

Transport for London. (2009). Business Case Development Manual. London: Transport for London.

Transport for London. (2013a). London Underground - Key Facts Retrieved 10.6.2013, from http://www.tfl.gov.uk/corporate/modesoftransport/londonunderground/1608.aspx

Transport for London. (2013b). London Underground upgrade plan Retrieved 10.5.2013, 2013, from http://www.tfl.gov.uk/assets/downloads/corporate/our-upgrade-plan-leaflet.pdf

Transport for London. (2013c). Transparency - Organisation Chart, from http://www.tfl.gov.uk/transparency/

9 List of figures

10 List of tables

11 List of abbreviations

MAST	Maintainability, Analysis, Spares, Tools
AC	Alternating current
BCV	Bakerloo, Central, Victoria lines
CM	Corrective maintenance
ET	Eddy current testing
FMECA	Failure mode, effect and criticality analysis
HPF	High positive friction
IM	Improvement maintenance
IMechE	Institution of mechanical engineers
JNP	Jubiliee, Northern, Piccadilly lines
LCC	Life Cycle Costing
LCF	Low coefficient of friction
LU	London Underground
MPI	Magnetic particle inspection
NDT	Non destructive testing
NoBo	Notified Body
NPV	Net present value
OEM	Original Equipment Manufacturer
ORR	Office of Rail Regulator
PDM	Predictive maintenance
PM	Preventive maintenance
RAMS	Reliability, Availability, Maintainability, Safety
REW	Name of the London Underground overhaul facility
ROSCO	Rolling Stock Owner
RTF	Run to failure
TfL	Transport for London
TOC	Train Operating Company
UT	Ultrasonic testing
VT	Visual testing

12 List of formulas

13 Appendix

Vehicle and Track Parameters which influence wheel life	Wheel Life Factors					
	Flange Wear	Tread Wear	Tread Plastic Deformation	Tread RCF	Wheel Flats	Differential Tread Wear
Wheel Load	yes	yes	yes	yes	Yes	yes
Vehicle Speed	yes	X	yes	X	Yes	X
Vehicle dynamics	yes	yes	yes	yes	X	yes
Wheel dynamic loads	X	X	yes	X	X	X
Track Quality	X	X	yes	X	X	yes
Route Curvature	yes	X	X	X	X	yes
Wheelset Rotational Movement	yes	yes	yes	yes	X	yes
Wheelset Lateral Movement	yes	yes	yes	yes	X	yes
Wheelset Set Up	yes	yes	yes	yes	X	yes
Flange Lubrication Efficiency	yes	X	X	X	X	X
Braking Methods and Characteristics	yes	yes	yes	yes	yes	yes
Effectiveness of Wheel Slip Protection	X	X	X	yes	yes	X
Wheel Re-Profiling Policy	yes	yes	yes	yes	yes	yes
Wheel Profile	yes	yes	yes	yes	X	yes
Rail Profile	yes	yes	yes	yes	X	yes
Rail Adhesion Levels	yes	yes	yes	yes	yes	yes
Train Operational Considerations	yes	yes	yes	yes	yes	yes

Table 36: Vehicle and track parameters which influence wheel life[107]

RSSB: Norm and Status	**Title of Standards**
Rail Industry Standards	
RIS-2701-RST Issue 1	Rail Industry Standard for NDT Processes on Rail Vehicles
Guidance Notes	
GMGN2646 Issue 1, March 2011	Guidance on Axle Bearing Maintenance
GMGN2646 Issue 1, Feb 2008	Guidance on Wheel / Rail Low Adhesion Measurement
GMGN2498 Issue 1 August 2008	Guidance on Wheelset Handling, Storage and Transportation
GMGN2497 Issue 1, December 2007	Guidance on Railway Wheelset Tread, Gauging and Damage Identification
GEGN8614, Issue 1, June 2011	Guidance on Axle box Condition Monitoring - Hot Axle box Detection

[107] Cassidy (2001, p. 296)

Codes of practice	
GMRC2494 Issue 2, February 2010	Recommendations for Railway Wheelsets Design
GMRC2495 Issue 1, August 2008	Recommendations for Railway Wheelset Manufacture and Assembly
GMRC2496 Issue 2, February 2010	Recommendations for Railway Wheelset Maintenance
European Standards	**Title**
EN 15313:2010	Railway applications- In-service wheelset operation requirements In-service and off-vehicle wheelset maintenance
EN 50126	Railway applications- RAMS
EN 60300-3-3	Life Cycle Costing Analysis

Table 37: A selection of Norms and Standards – RSSB and EUROPEAN standards

LUL standards	Description
E6340	Engineering of rolling stock wheelsets and wheelset bearings
E6347	Rolling stock wheelset tread standards and gauging
E6831	Train maintenance regime
E6341	General requirements for new wheelsets
E6342	Rolling Stock axles
E6343	Rolling Stock wheels
E6348	Rolling stock wheelset bearings
E6344	Non-destructive testing of rolling stock wheelsets
E6345	Protection of rolling stock axles
M 6344 A3	Non-destructive testing of rolling stock wheelsets

Table 38: London Underground wheelset standards

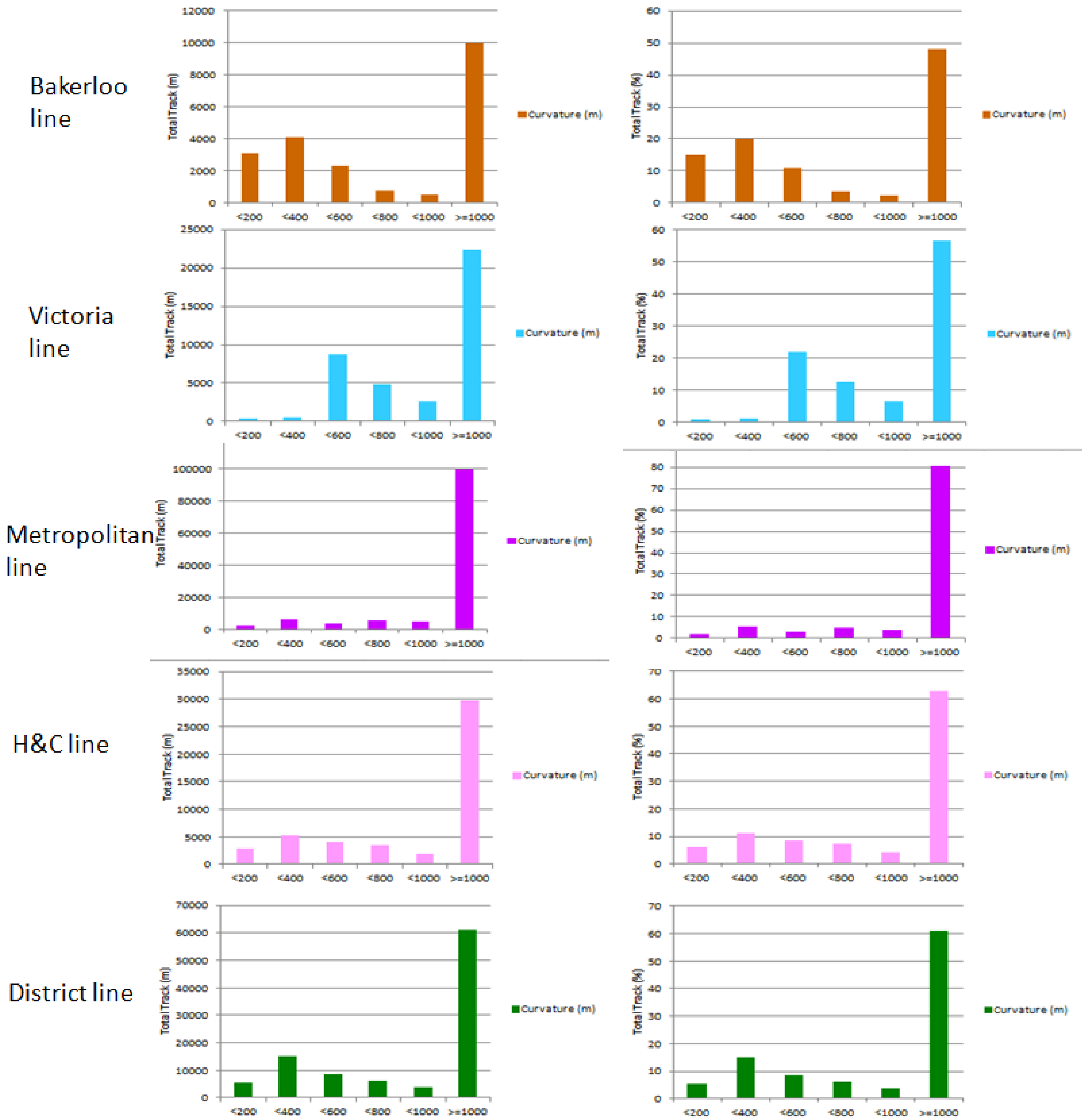


Figure 74: Track data of London Underground[108]

[108] Received from LU, 11/2013

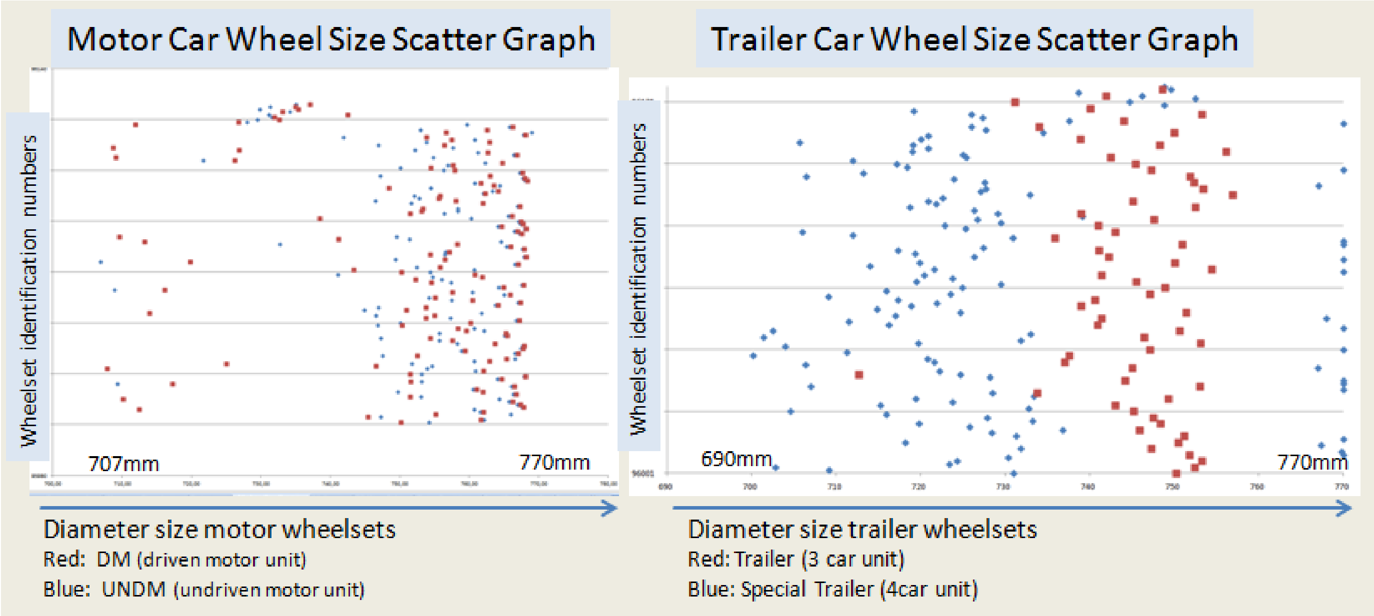


Figure 75: Distribution of wheel diameters from a LU fleet in operation[109]

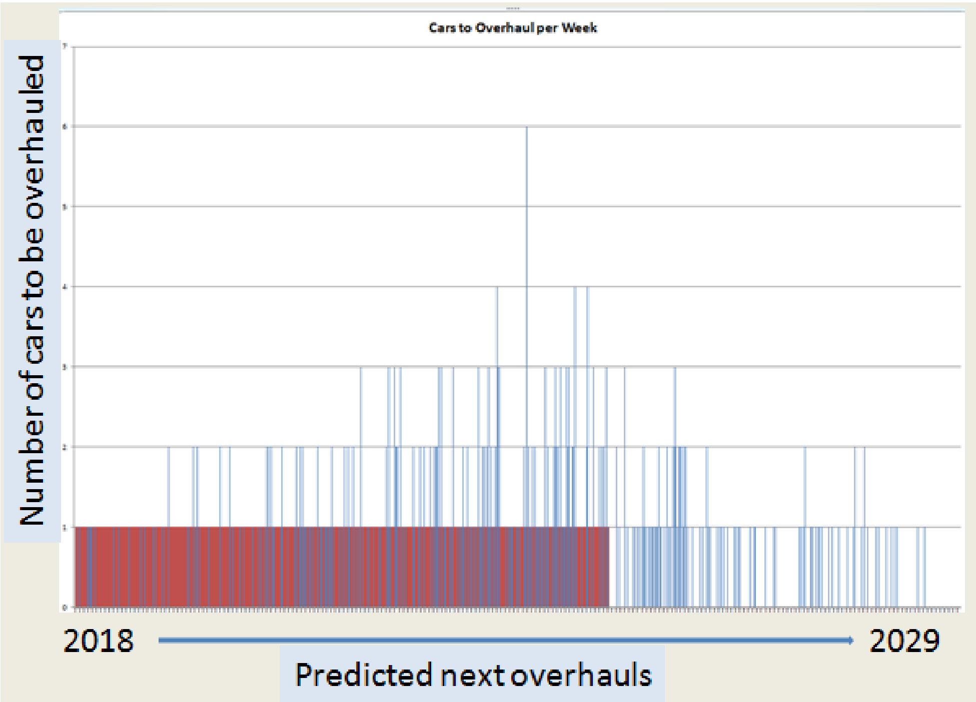


Figure 76: Normal distribution of predicted wheelset overhauls based on the measured wheel diameters[110]

[109] Received from LU, 10/2013
[110] Received from LU, 10/2013