NeTIRail

Needs Tailored Interoperable Railway Infrastructure

Deliverable D1.4

Cost and User benefit report

Submission date : 22 March 2018

NeTIRail-INFRA is funded by the European Commission under the Horizon 2020 programme - Grant agreement n° 636237

Lead contractor

University of Leeds

Project Coordinator

University of Sheffield, USFD

Executive Summary

This deliverable presents the analysis of the effects on costs and user benefits of the innovations developed in the NeTIRail-INFRA project. The report can hence be described as a detailed economic assessment of the NeTIRail-INFRA railway innovations. Cost-Benefit Analysis is the central methodological framework utilised for this task.

In most (if not all) industries, technological innovations may improve efficiency and productivity and can make goods and services more accessible to all. This certainly holds true for the transport sector and, in particular, the railway – the context of our research. However, the implementation of engineering technologies often comes with great uncertainties and can involve substantial amount of investment. Therefore, an economic understanding of the implementation and impacts of technologies is necessary but non-trivial: it involves a series of challenges which have surprisingly received little attention in the literature. This is particularly relevant to the railway industry where technical leaps may be very costly and where it accordingly is all the more necessary to provide both a financial rationale (for the infrastructure provider) as well as a wider economic motive for large investments. Obtaining the aforementioned economic understanding of the NeTIRail-INFRA railway innovations is the purpose of this deliverable.

This deliverable will feed into Deliverable 1.8, where all the elements of the economic and social assessment of the NeTIRail-INFRA railway innovations - developed in this (D1.4) and previous Deliverables D1.6, D1.7, D5.2 and D5.3 – are brought together; namely, the core Cost-Benefit Analysis contained in the present deliverable, (D1.4), the societal analysis (D5.2 and D5.3), the wider economic impact assessment (D1.6) and the research on incentives for the implementation of innovations (D1.7).

Since there are a variety of innovations which can also be applied independently from each other, the analysis is conducted separately for each innovation or group of innovations. The report is divided into three main blocks, one for each work package (WP2, WP3, and WP4) and where each WP contains several innovations.

Following the introduction, Section 2 presents a brief description of each innovation. In Section 3 the methodology is explained. Sections 4, 5 and 6 contain the economic appraisal for all innovations. The concluding remarks are provided in Section 7.

No major deviations in relation to the NeTIRail-INFRA Grant Agreement are reported. However, one minor observation that should be noted is a shift in the focus from travel demand to infrastructure and operational costs. At the time of writing the Grant Agreement, technologies had not been developed and hence it was uncertain to what extent they would impact costs and user benefits. Over the course of the project it became clearer that cost analysis was going to have a more prominent role than user benefit analysis. This shift is reflected in this deliverable.

Table of contents

Abbreviations and acronyms

Abbreviation / Acronym	Description
ABA	Axle Box Accelerations
BCR	Benefit-Cost ratio
CBA	Cost-Benefit Analysis
D	Deliverable
DM	Do Minimum
DN	Do Nothing
DS	Do Something
IM	Infrastructure manager
LCC	Life Cycle Costs
M&R	Maintenance and renewal
NPV	Net Present Value
OLE	Overhead line
PVB	Present Value of Benefits
PVC	Present Value of Costs
S&C	Switches and crosses
T	Task
VoT	Value of Time
WP	Work Package
WTP	Willingness-to-Pay

1. Introduction

1.1 Task description

Quoting from the NeTIRail-INFRA grant agreement Annex 1 (Part A – section 1.3.3 WT3 Work Package Descriptions, p.12):

> *This task focuses on developing a strategic, top-down cost model that estimates the impact of the relevant technologies on whole life costs. This assessment will be made against a baseline of existing costs. The costs will be context specific. Further, a high level, strategic approach will be adopted, in line with the needs of the project.*

The first part of the overall task was reported in Deliverable D1.3, which outlined the cost modelling approach. In Deliverable D1.4, that method is applied to the different case studies for the different innovations, jointly with the analysis of user benefits. D1.4 therefore builds upon deliverables D1.1, D1.2 and D1.3, but is written in a way that can be read as a standalone piece of research.

1.2 Scope and structure of the report

The aim of D1.4 is to present a cost-benefit analysis for the railway innovations developed as part of the NeTIRail-INFRA project. All potential effects of the interventions on cost and benefits are to be identified as well as measured and valued where feasible. Since much information that is required for this purpose is not available, the text must at several instances rely on data and econometric analysis from other countries and on a principal line of reasoning, including asking what the annual cost savings would need to be to make the up-front investment costs worth it from an economic perspective (where the former are unknown; this approach being referred to as the Switching Values Approach). In these parts of the presentation, the purpose is to establish what the analysis would look like if comprehensive data was available. It is common in cost-benefit analysis to work with incomplete information, and the Switching Values Approach is utilized also by the UK Department for Transport (DfT); see DfT, 2017.

Section 2 presents a brief overview of each of the innovations, followed by a description of the methodology for cost-benefit analysis in Section 3. Section 4, 5 and 6 contain the analysis on costs and benefits for the innovations from WP2, WP3 and WP4 respectively. Each WP deals with a set of innovations that share common features; e.g. WP4 innovations are primarily focused on rail track monitoring techniques. The final Section 7 provide concluding remarks on the economic assessment of the NeTIRail-INFRA railway innovations and sets out the generic structure of the methods that can be used to conduct an economic assessment of technical improvements.

2. Description of the NeTIRail-INFRA innovations

The NeTIRail-INFRA project comprises the development of a wide range of technological innovations for the railway. The innovations cover and address multiple aspects of the railway infrastructure, such as inspection technologies, renewal processes, materials, maintenance activities and electrification. They also spread across a range of Technology Readiness Levels (TRLs), as defined by the European Commission guidelines. Some innovations are truly novel (TRL 1-3), e.g. trolley wire for overhead line or new designs for transition zones; some are somewhat more developed (TRL 4-7), such as the Axle Box Acceleration, on track monitoring, smart phone monitoring, tailoring wire tension and tailoring track to avoid corrugation; and others are really just the application of technology (TRL 8-9), i.e. technologies that are known and fairly mature, where the innovation has been to apply existing technology and techniques and advise on what is most appropriate for different locations, e.g. lean techniques for S&C assembly and installation.

All details on each of these innovations can be found in their respective WPs and Deliverables. This section only provides a short description for each innovation as background information, to enable a better understanding of the economic evaluation.

2.1 Innovations from NeTIRail-INFRA WP2

2.1.1 Overview

The innovations of WP2 aim at improving the existing tracks to optimise the overall use of resources. The term “resources” can be seen from a broad perspective. The core component is the maintenance costs over the life time of the assets, but resources may also be taken to include an impact on users. Thus our definition of resources can include both costs for train operators, infrastructure managers and for the final customers, i.e. travellers and freight customers, e.g. in terms of delayed services.

Four innovations are considered within this work package:

- Lean techniques for S&C
- Tailoring track (clips and pads) to avoid corrugation
- Optimal lubrication techniques
- New design for transition zones

2.1.2 Lean techniques for S&C (Task 2.3)

The focus in this task is on the techniques used when repairing or replacing existing switches & crossings (S&C). The concept of lean techniques derives from the automotive manufacturing field, the intention being to apply cost-efficient techniques in every dimension of the production process. In its railway application, it mainly refers to the reduction of track possession time for implementing maintenance and investment activities and to optimize the related effort. Three alternative ways for renewal are considered, each of which has the potential to be optimized:

- off-site assembly and transport to the site of a new switch;
- trackside assembly; and
- on-track assembly.

It should be noted that 'lean techniques' are commonly used in the automotive industry and in manufacturing environments, these same techniques have been applied to the processes around switch and crossing maintenance and renewal. The solutions suggested are not necessarily novel, but an application of technology and processes to reduce waste in the process. The innovation here will look at further optimization of one particular process and comparison across different approaches, based on a specific context. It is expected that lean techniques can (at no monetary cost) provide substantial productivity and efficiency gains to the railway.

2.1.3 Tailoring track to avoid corrugation (Task 2.4)

This task aims at providing a theoretical understanding of what causes short pitch corrugation and suggesting changes in the rail track to reduce the problem, namely by looking at different clips and pads.

The way in which clips and rail pads, i.e. the fastening system, functions may explain corrugation initiation. The engineering aim of this task is to provide a theoretical understanding of what causes (short pitch) corrugation. Identification of corrugation drivers opens the possibility to design the fastening system as well as tracks and sleepers in a way that reduces the need for maintenance and potentially renewals.

This means that the economic issue at hand is related to a comparison of the consequences of using different types of clips, pads, etc. for avoiding corrugation.

2.1.4 Optimal lubrication techniques (Task 2.5)

An efficient lubrication of the wheel-rail interface can reduce rail and wheel wear as well as energy consumption, leading to substantial cost savings (Reddy et al., 2007). Quoting NeTIRail-INFRA Deliverable D2.7, "correct and proper management of the rail–wheel interface helps the rail industry to reduce wear and fatigue, which results in enhancement of asset life, growing of rail industry's business and improving reliability of service. In the case of railway curves, properly and efficiently applied lubricants decreases squeal on corners and reduce rail noise. Similarly, correctly applied lubricants can reduce wear on track and wheel, particularly on the contact zone on the outside curve".

The background to this task derives from technical limitations of a pumping system in use in Turkey. While this particular challenge has now been solved, the development of solutions has – except for providing some quantitative evidence – resulted in testing of further innovations. Several issues have been addressed as part of the NeTIRail-INFRA project: when, how and how much lubrication should be used? Which type of lubricant?; Is it best to use a track based or an on-vehicle system? A new on-board lubrication system has been tested in Slovenia and the economic assessment will illustrate what its impacts might be for the railway.

2.1.5 New design for transition zones (Task 2.6)

Maintenance in transition zones is more expensive than on plain lines, and existing transition zones technology does not help to make the rail components last long enough. The purpose of this innovation is to reduce displacement that occurs in these zones. The NeTIRail-INFRA innovation for transition zones is concerned with changing the design features of transition zones. This could relate to the position, shape and mass of sleepers, with the objective of reducing the displacement. The economic analysis is therefore concerned with comparing life cycle costs of two approaches to transition zone design; the current and the alternative design.

NeTIRail-INFRA research suggests the use of more (heavier) sleepers per transition zone. Through lower displacement, settlement (and RCF and wear) conditions are improved, and less maintenance (tamping and grinding) is needed. Also, the life of the rail assets lasts longer (fewer renewals).

2.2 Innovations from NeTIRail-INFRA WP3

2.2.1 Overview

The overall goal of WP3 is to develop technology to enhance the life-length of the overhead line power supply infrastructure and reduce the life-cycle costs. It focuses on the challenges which lead to delay through unreliable performance of overhead line power supplies, the investment costs which make it difficult to install overhead power on low density railway lines, and on the ongoing operational cost of maintaining the system. Three innovations are considered to achieve these goals:

- Trolley wire model, which is a simplified overhead line system to be installed on lesser used lines to reduce capital expenditure
- Optimised wire tension, which aims to reduce failure and costs simultaneously
- On-board monitoring of the overhead line, which facilitates performance maintenance to be tailored to the lowest life cycle cost

2.2.2 Trolley wire model

The first innovation is concerned with renewal and considers alternative designs when lines are electrified or when existing overhead equipment is to be replaced. The trolley wire model is proposed as a simplified overhead line system to be installed on low density lines to reduce life cycle cost. Figure 1 shows a typical span of rail overhead power line (the catenary wire model). A tensioned contact wire is suspended, approximately parallel to the track beneath, from a catenary wire that is itself tensioned and supported by fixed masts. Electric trains are fitted with a pantograph that runs along the contact wire and current is drawn across the sliding contact between the two.

The proposed trolley wire model is shown in Figure 2. Compared to the catenary wire model, the trolley wire model involves a much less complicated structure while following similar general geometry. Instead of relying on the combination of catenary wire and contact wire to supply the power, the trolley wire model requires only the contact wire. The catenary wire and droppers are omitted in the new model. However, the new model needs more masts to support the standalone contact wire. Instead of 60m in the catenary model, the trolley wire model needs a mast in every 32m’s distance along the railway line, which means that on average the usage of masts would double in the trolley wire model.

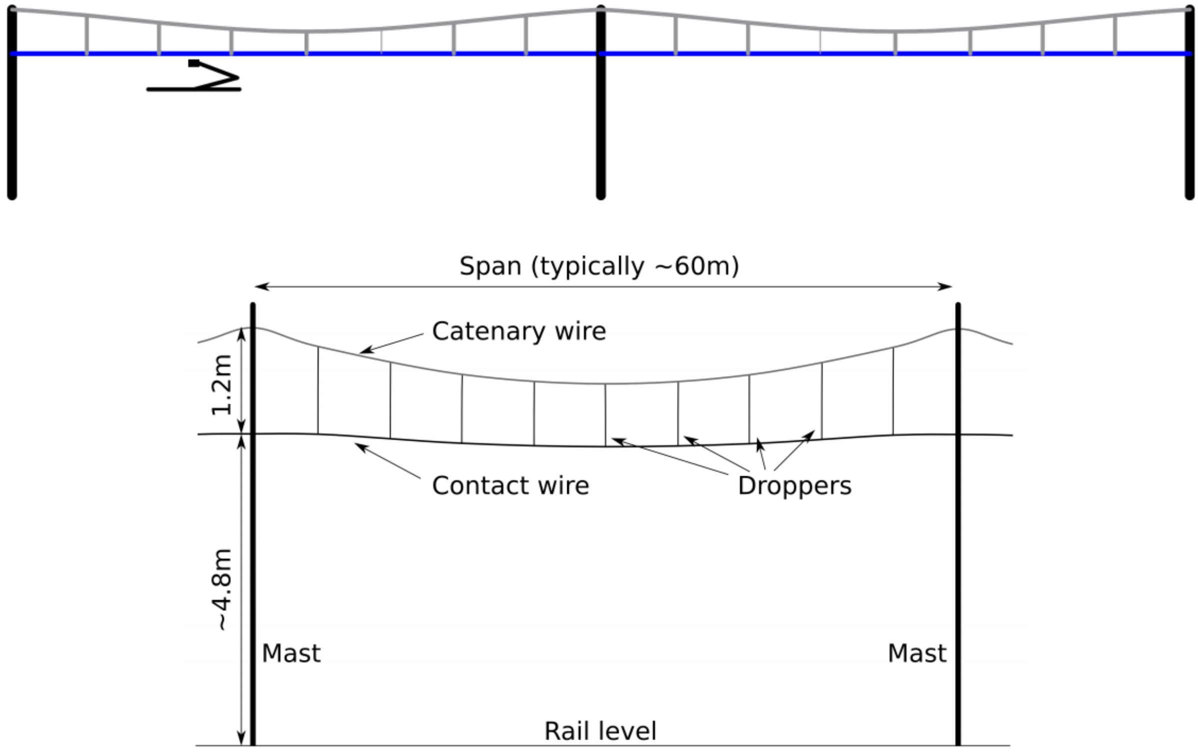


Figure 1. Catenary wire model

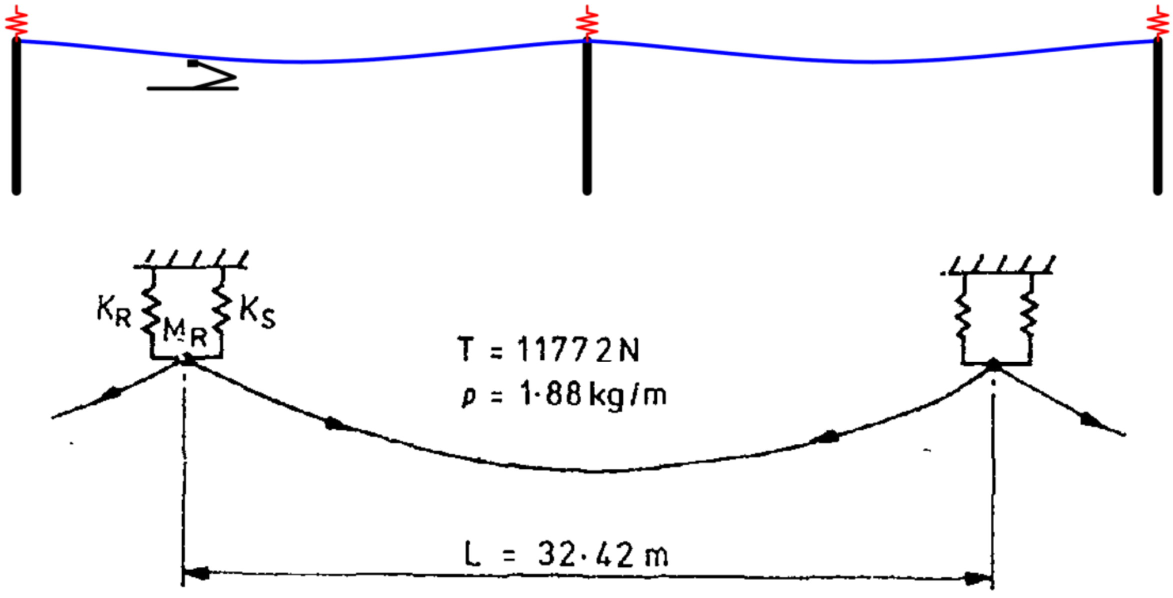


Figure 2. Trolley wire model

The trolley wire model has been implemented in tram systems and the associated costs of construction and maintenance can be adopted to our case studies. Since the new system cannot be used for high speed lines due to the greater sag in the wire, we will focus on the cases where the model is applied on secondary lines. The CBA will evaluate the impact on the secondary lines in Romania and Slovenia which are not yet electrified.

It is expected that the trolley wire model with simpler system will involve cheaper installation costs with the same span, less displacement with decreased cross section area, cable tension and pantograph force, but more displacement of pantograph, greater risk of fatigue, and more costs on mast installation.

2.2.3 Optimised wire tension

The second innovation is related to optimization of existing equipment by way of considering the appropriate tension of the overhead wire. Wire tension is one of the controllable factors for overhead lines which influence the life cycle costs and maintaining the overhead line performance. The analysis is concerned with establishing the wire tension that optimises asset life and life cycle costs to be applied on the traditional overhead line system. It is expected that increased wire tension will result in smaller defections of the contact wire, reduced fatigue of the overhead line system and more rapid crack propagation, whereas less tension means less risk of tensile failure.

2.2.4 On-board overhead lines monitoring

The third innovation is related to monitoring the electrical properties of the overhead line system. It focuses on two major parameters: the voltage at the entrance to the train from the pantograph, and the current absorbed through the main transformer. High sampling rate of the collected data will allow the system to recognise rapid changes in the current absorbed from the railway power supply system, through pantograph. Knowing a complete image of the electrical parameters and the quality of the electric contact between pantograph and contact line, optimisations could be made. Also, structural failures not only on the contact wire but also on the carbon stripe of the pantograph could be detected earlier.

2.3 Innovations from NeTIRail-INFRA WP4

2.3.1 Overview

The innovations of WP4 aim at enhancing the monitoring capabilities of the railway, ultimately to save on life cycle costs. Tasks 4.1 to 4.3 focus on track side registration of vibration of switches and plain line and the facilitation of early defect detection and ride quality, through various monitoring devices. Task 4.4 focuses on task automation in interlocking and communication (sensor data transmission). The tasks of WP4 generate the following innovations which will be evaluated in this deliverable from an economic perspective:

- 4.1 On-track monitoring
- 4.2 ABA, on-train monitoring
- 4.3 Smartphones, on-train monitoring

The strategy for the evaluation of Tasks 4.1, 4.2 and 4.3 is based on development of the current approach for monitoring the quality of train services. The contemporary means for quality monitoring makes use of measurement trains that pass over main lines a couple of times per year to register track quality in several dimensions. This means for quality measurement is costly, meaning that it is rarely used on lines with little traffic. Except for this mechanised approach, quality is checked manually by members of the maintenance crew as well as by locomotive drivers that detect irregularities. It is important for the interventions considered in this WP to recognise that it is typically not feasible for staff to detect irregularities until they are severe, even posing a risk for train closure at detection and – the worst outcome – derailment. In general, if the Infrastructure Manager (IM) is better informed about track quality it is possible to increase preventive maintenance and accordingly to reduce corrective maintenance, with all the associated consequences in terms of costs, reliability, availability and safety.

New rolling stock on high-standard railway lines are generally equipped with technology that monitors the movements of the rolling stock as default installations. It is possible that this information could also be used for track quality measurement. However, since modern rolling stock is rarely used on secondary lines, it is not relevant for many of the lines in focus of the NeTIRail-INFRA research.

2.3.2 On-track monitoring for turnouts and S&C (Task 4.1)

The purpose of this innovation is to obtain more regular and precise information about rail defects around the turnouts S&C sections, which are particularly susceptible to defects since these have an accelerated wearing process and short time between renewals. This will be done by using specific monitoring devices. These devices are complementary to those from tasks 4.2 and 4.3, described immediately after this section.

While this vibration monitoring system first and foremost targets S&C segments, it is also useful for plain lines. This is then an additional benefit of a functioning system that is not part of the subsequent evaluation.

The system developed in T4.1 monitors the vibration of the rails at a specific level. When the shape and amplitude of the vibrations are changed this provides an indication of deteriorating performance. As vibrations become increasingly severe, this will eventually trigger maintenance activities. The ultimate purpose is that the monitoring devices will help triggering the intervention at an earlier point of time that under the do-minimum strategy, i.e. a switch from a reactive to a less costly preventive action.

2.3.3 ABA, on-train monitoring (Task 4.2)

Task 4.2 considers the use of an on-train monitoring equipment referred to as ABA. This equipment requires a costly installation but will, on the other hand, provide detailed information about the condition of the rail by registration of vibrations in different dimensions. This means that it is possible to collect continuously the relevant information to detect local rail defects before they have become too severe, much in the same way as the on-track devices in task 4.1. Summarising, the innovation provides a second way of obtaining rail health condition information.

2.3.4 Smartphones, on-train monitoring (Task 4.3)

In the same way as for task 4.1 and 4.2, the purpose of this innovation is to obtain regular and precise information about rail vibration, lateral acceleration, roll velocity, etc. But in the case of this particular technology, one immediate benefit is that it will be possible to estimate the passengers' perception of ride comfort (see Figure 1) and to improve the quality of using the train service. The same equipment is also to be used for identification of defects in the infrastructure.

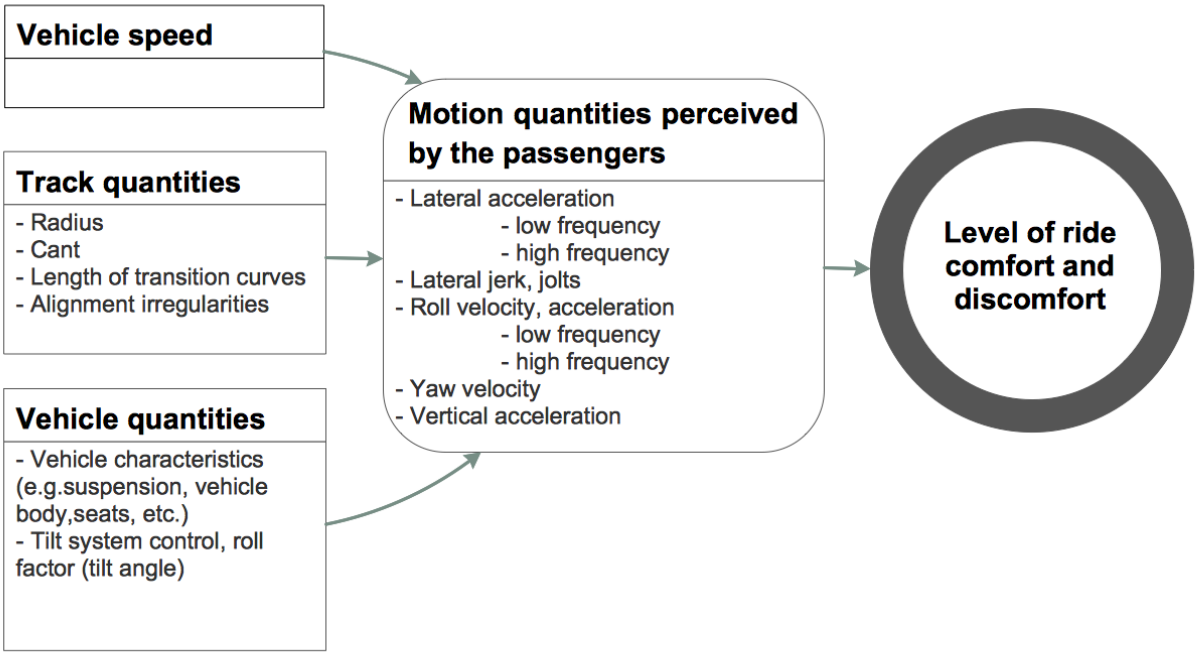


Figure 3. Certain track and vehicle quantities and related motion quantities that have ride comfort and discomfort responses

The use of ABA (cf. task 4.2) is more accurate than smartphones in detecting defects. At the same time, it is more costly and difficult to install. It may also take longer time to interpret data than if a smartphone is used. It should, however, be noted that the second part of task 4.4 proposes a solution to reduce or eliminate this difference.

The basic idea is thus that the smartphone solution is less accurate in defect detection, is a cost-efficient way to detect passenger comfort issues and to identify some but not all infrastructure defects. Depending on the situation on each line and on the purpose of the data analysis that the rail administration wants to perform, there is a choice to make between the two options.

Summing up, from an economic perspective, the main benefit of this system is the provision of frequent information on track health condition that allows some preventive tasks to be undertaken. This can lead to reductions of delays and allow the IM to reduce Temporary Speed Restrictions (TSR) which might be linked to uncertainties about track condition. Additionally, the information can be used to detect ride comfort issues and improve passengers' experience.

3. Methodology overview

The overall methodology used to assess the economic impact of the railway innovations is outlined in this section (see also Deliverable D1.2 and D1.3). Since the application of the methodology varies slightly for each innovation, due to their different nature and also data limitations, the application of the methodology can vary by context. Therefore, adaptations of the method will be presented under each block of analysis in the respective sections.

3.1 The Cost-Benefit Analysis (CBA) framework

The NeTIRail-INFRA project offers a series of innovations for the railway infrastructure. The innovations are expected to have impacts (in terms of changes in costs and benefits) on society, but particularly on different groups: infrastructure managers (IMs), train operators (freight and passenger) and railway end users. The CBA analysis takes the perspective of the overall society since it aims at accounting for every possible impact. For this reason, we can refer to this also as Social CBA. At the same time, we are also interested in the recipients of each cost and benefit. Therefore, our CBA analysis also includes a stakeholder assessment, where each impact is associated to a specific agent in the economy. The two elements of the CBA can be summarised as follows:

- A socio-economic CBA, covering all affected parties (i.e. society).
- A financial CBA, analysing the impacts on each of the relevant stakeholders.

It is useful to note the link to WP5 here. WP5 is concerned with a societal analysis of the innovations. Hence, the societal angle is shared between WP1 and WP5. The difference lies in the type of analysis that is conducted under each WP. Here we focus on the economic analysis using a Cost-Benefit Analysis, whereas WP5 uses a non-monetary quantification strategy and introduces questions of equity into the analysis by, for instance, looking at the *distribution* of costs and benefits inside a given stakeholder group. See the NeTIRail-INFRA Deliverable D5.1 "“Societal and legal effects of transport decision: stakeholder analysis” and NeTIRail-INFRA D5.2 “Perception of different service options: User study and data analysis. Moreover, CBA results typically net out effects where one group benefits the same amount that another group loses. Deliverable D5.3 will integrate WP1 and WP5 results. WP1 and WP5 analyses are complementary and warnings of double-counting risks are made where appropriate.

The table below includes a generic description of impacts and groups that could be considered for railway projects. In the case of the NeTIRail-INFRA innovations, only a subset of these groups and impacts will be relevant.

Table 1. Social and Stakeholder CBA – Impacts table

	Groups			
	IMs	**Train Operators**	**End users**	**3rd Parties**
Impacts	Changes in costs and revenues	Changes in costs and revenues	Changes in costs and benefits for passengers and freight users (e.g. improvements in reliability, availability, safety, etc.)	• Environmental externalities (CO2, noise). • Government: grant or subsidy requirements • Residents (connectivity, noise…) • Wider economy

Note that some of the benefits and costs of the innovations appear more than once in the table above (e.g. imagine a change in the price for the passengers that would also be a change in revenue for the operator). The aim here is simply to identify and quantify all impacts; the construction of the CBA will deal with the addition of impacts afterwards to avoid double counting (some impacts may simply be transfers from one group to another, and this will be accounted for adequately within the analysis).

The CBA will be developed for each of the case studies separately. This means that what the CBA will measure is the net benefit of each innovation for a given railways line/s. In general, after having conducted the analyses, the most relevant impacts for the innovations (from the more comprehensive table 1 above) can be summarised into three categories: investment costs, life cycle cost savings and end-user benefits. These three categories will determine the output of the CBA for each innovation:

Table 2. Main cost and benefit categories

Costs	Benefits
• Investment costs	• Life cycle cost reductions • End-user benefits

The outcome of a CBA would be positive if benefits outweigh the costs (figure 4)

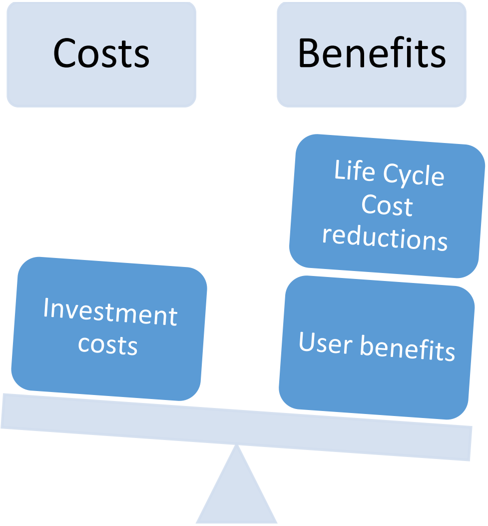


Figure 4. CBA: contrasting costs and benefits

To develop the CBA, the starting point is the definition of the baseline scenario, also called the Do-Minimum scenario. The baseline should represent the most likely situation of the railway line if the innovations are not applied (i.e. the current context). Secondly, a Do-Something scenario should be defined precisely, e.g. as the situation of the railway line if one particular innovation is applied. Note that there is a scope to consider several different Do-Something scenarios. The following graph summarises the key steps in the development of the CBA assessment.

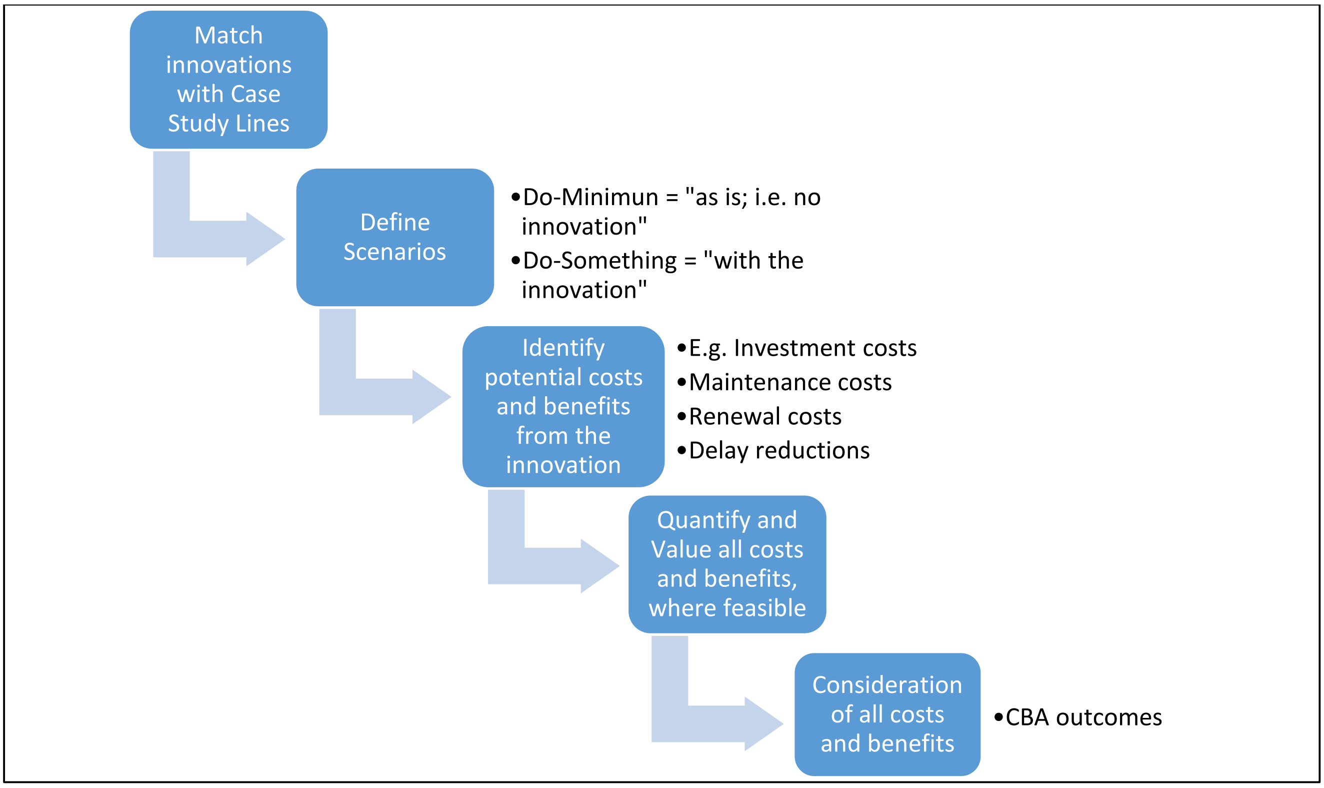


Figure 5. Key steps in CBA

3.1.1 CBA key parameters

For all case studies and all scenarios, the following parameters are selected to underpin the analysis:

- **Time horizon**: the analysis is performed for a chosen year-period, which can vary by innovation. The choice will depend on the asset life of the innovation considered and the life of assets in the do-minimum scenario. For example, for most innovations in WP4 a 10-year period is considered, since that is the life of the monitoring device with longest life. In some cases (e.g. lean techniques for S&C), however, the innovation itself does not have any specific asset life and it does not affect the life of any rail components. The decision made for each case will be justified when it departs from the generic approach of using the longest asset life. It should be noted that this approach is a deviation from standard CBA guidelines, where a fixed time horizon is pre-determined (e.g., 60 years in the UK; DfT, 2016). The purpose of fixing the time horizon for all projects in the standard guidelines is to allow comparison between the many different investment schemes that Government must choose from. However, this is not necessary here, where the aim is to present the economic analysis of each independent innovation in the clearest and simplest way to any interested parties (IMs, public sector, operators, researchers, etc.). Using the relevant asset life/s facilitate this goal.
- **Discount rate**: the analysis is built assuming a 3% discount rate. This assumption is in line with common practice in Europe and is recommended in the CBA guidelines by the European Commission (European Commission, 2014).
- **Indirect tax correction factor**: 1.190 (DfT, TAG Unit A1.2, p.21). This follows the WebTAG guidelines (Department for Transport, 2016). WebTAG is the UK Department for Transport (DfT)'s transport scheme appraisal guidance. Quoting WebTAG (DfT, 2014, TAG Unit A1.1 Cost-Benefit Analysis, p.16) "indirect taxation creates two possible units of account for CBA: market prices (gross of indirect tax) and factor costs (net of indirect tax). Businesses and government, which do not pay indirect tax, perceive costs in the factor cost unit of account while consumers perceive market prices. What is important for CBA is not which is used but ensuring all impacts are presented in consistent units. The indirect tax correction factor is the conversion between the two units. Transport CBA uses the market prices unit so a correction factor has to be applied to costs or benefits that have been measured net of tax".
- **Inflation adjustment**: 1.0277 (using ratio of RPI index from years 2014 and 2016, to convert data provided from 2014 into 2016 prices). All final values are provided in 2016 market prices. The reason for doing this is to have all CBA monetary elements in the same year prices and to apply the same base year across different project evaluations (in this case, 2016), which facilitates comparisons.

3.1.2 CBA output table

The expected outcomes of the CBA analysis can be presented, in a generic manner, in the following table. The table has been tailored to an overarching view of all innovations analysed. As we shall see in each of the detailed analyses, the final output table varies considerably from case to case to adapt to the particularities of each case study.

		Costs and Benefits output table			
		Innovation 1		**Innovation 2**	
		Time horizon=10 years ; @3% discount		Time horizon=10 years ; @3% discount	
Costs (by stakeholder)					
Infrastructure Manager					
Capital investment costs					
Maintenance costs					
Other costs					
Total Costs					
Benefits (by stakeholder)		Sensitivity scenario 1	Sensitivity scenario 2	Sensitivity scenario 1	Sensitivity scenario 2
Infrastructure Manager					
Life cycle cost (LCC) savings (M&R)					
Increased track availability					
Total benefits for IM					
Rail users					
Delay reductions					
Safety risk reductions					
Comfort improvement					
Total benefits for rail users					
Total benefits					
Social CBA outputs					
Net Present Value (NPV)					

Figure 6. Generic CBA output table for NeTIRail-INFRA innovations

In some instances, some impacts cannot be monetised or estimated with sufficient confidence. If those impacts are central to the appraisal of the innovation, it will not be possible to obtain a realistic and credible estimate of the overall NPV. In those cases, the 'switching values' approach will be used (see DfT Value for Money Framework, 2017). The 'switching values' approach evaluates what change in the Present Value of Benefits (or Present Value of Costs) is necessary to achieve a predetermined level of NPV (for example, NPV equal to zero). The analysis will be complemented with a judgement of how likely this change in PVB (or PVC) is to be realised.

4. Cost-Benefit Analysis of WP2 innovations

The innovations of WP2 aim at improving the existing tracks to optimise the overall use of resources. Resources are seen from a broad perspective. The core component is the maintenance costs over the life time of the assets, but as noted earlier, our definition of resources may also include an impact on users. These can be costs for train operators, infrastructure managers and the final customers, i.e. travellers and freight customers, e.g. in terms of delayed services.

Four innovations are considered within this work package:

a) Lean techniques for S&C
b) Tailoring track (clips and pads) to avoid corrugation
c) Optimal lubrication techniques
d) New design for transition zones

4.1 Overview of CBA Scenarios

The aim of the CBA is to quantify and compare the cost and benefit profiles with and without the innovation, over a given time period of the case study. Different case studies will be used to assess each of the innovations from WP2. In all cases, the Do-Minimum scenario will represent the state of the railway as it currently is (i.e. without any innovation). Hence, conceptually we can define specific Do-Something scenarios for each innovation – even though each will be tailored to a specific (different) case study. We define these scenarios as follows:

i) Baseline scenario (Do-Minimum): characterised by the current railway technology and processes, including maintenance activities of the current technology.
ii) Do-Something Scenario (DS): characterised by the **introduction of a new technology or process** that aims at making the railway more efficient and/or reduce the risk of damage in the tracks. Whereas the idea is that each innovation (e.g. innovation x) is defined by one Do-Something scenario (e.g. DSx), in some cases more than one DS scenario is considered to accommodate small variations in the innovation (e.g. DSx.a and DSx.b). The full list comprises:
    - DS1a: off-site assembly and transport to the site of a new switch, with lean techniques (relative to DM: Off-site assembly and transport to the site of a new switch).
    - DS1b: S&C trackside assembly, with lean techniques (relative to DM: Off-site assembly and transport to the site of a new switch).
    - DS2: Use of a different type of clips and pads (relative to DM: current clips and pads)
    - DS3: On-board lubrication (relative to DM: current lubrication technique)
    - DS4: heavier sleepers for transition zones (relative to DM: current design)

Note that this notation (DSx) is only used here in the introduction to WP2 technologies, to provide an overall picture of the DS scenarios evaluated. However, for each sub-section (e.g. 4.2, 4.3 and so on), the DM scenario will always be contrasted with DS scenarios renumbered in each case (e.g. DS1 and DS2 if there were two DS scenarios for one given technology).

The time horizon will be different for each DS. This choice is driven by the asset with longest life. It is worth emphasising that the use of different time horizons for the respective innovations is methodologically consistent. Each new technology is considered in isolation from the others, and the result indicates whether that intervention is justifiable in economic terms. Two or more innovations may be warranted, or indeed no-one of the options considered. What is of importance for the analysis is for the life of all technical components to be consistent *within* each innovation, while different innovations can have different time horizons.

4.2 CBA of Lean techniques for S&C

The focus in this task is on the techniques used when repairing or replacing existing switches & crossings (S&C). The concept of lean techniques derives from the automotive manufacturing field, the intention being to apply cost-efficient techniques in every dimension of the production process. In its railway application, it mainly refers to the reduction of track possession time for implementing maintenance and investment activities and to optimize the related effort. Three alternative ways for renewal are considered, each of which has the potential to be optimized:

- Off-site assembly and transport to the site of a new switch;
- trackside assembly; and
- on-track assembly.

It should be noted that these methods already exist and the innovation will look at further optimization and comparison across different approaches. Since the level of optimization for these processes varies across countries, the definition of the Do-Minimum is contextualized for the case study selected for the application of lean techniques: Turkey. While in some European contexts (e.g. UK) it may be possible to find a high level of optimization for S&C replacement processes, lean techniques are not widespread across Europe, causing avoidable inefficiencies to railway systems. In Turkey, researchers from NeTIRail-INFRA conducted on-track observations to reveal current practices (Kayseri, Turkey). The standard approach consists of off-site assembly and transport to the site of a new switch.

The Do-Minimum (DM) and Do-Something (DS) scenarios will be defined as follows.

- DM: off-site assembly, transport to the site of a new switch and installation
- DS1: off-site assembly, transport to the site of a new switch, and installation with lean techniques.
- DS2: S&C trackside assembly, and installation with lean techniques

A third DS scenario (DS3: S&C on-track assembly, with lean techniques) has not been fully developed due to lack of observations in the empirical trials performed as part of WP2. Nonetheless, the principles are the same as for the other DS scenarios and therefore the framework could easily be applied when data becomes available.

It must be noted that the applicability and effectiveness of lean techniques will be dependent on the site location. For instance, achieving high level of efficiency might be more difficult in locations which are further away from a station due to logistic limitations.

4.2.1 Do-Minimum Scenario

Current practice consists on off-site assembly of the new switch and transport to the site to be installed. The following information further describes the DM scenario.

Pre-assembly work and installation

According to the observations, the off-site assembly of one switch takes approximately 2 hours and the installation takes 6 hours and 40 minutes.

Switch components, sleepers and ballast

The total material costs for one S&C is €5,000 based on information from the track engineers.

Backhoe loader hire

Two machines at €150 each including operators are needed to cover a shift. This data is based on information from the track engineers.

Number of labourers

11 workers are needed per shift for the assembly process and also for the pre-assembly process.

Labour rate

The following salaries are an average representation of the Turkish context[1]:

Low skilled – 1380 TRY/month = 290€/month = 1.67€/hr (based on a 40hr week)

High skilled – 2830 TRY/month = 594€/month = 3.43€/hr

The workers employed for this task are likely to be somewhat in-between the two categories. Hence, we assume an average wage rate of 2.55€/hr applies.

Volume of switch renewals per year in Turkey

Approximately 750 S&C are renewed per year, based on estimate by track engineers in Kayseri.

The table below summarises the details and costs of the Do-Minimum scenario for the assembly and installation of a S&C in Kayseri.

Table 3. Lean techniques for S&C: Do-Minimum scenario information & Costs

Do-Minimum						
		Wage	**Hours needed (per shift)**	**Cost (€,2017)**	**Units needed**	**Total Cost**
Switch unit cost		NA		5000	1	5000
Backhoe loader hire		NA		150	2	300
Installation shifts		28.05	9	252.45	1	252.45
	Workers	*2.55*	*9*	*22.95*	*11*	*252.45*
Pre-assembly work		2.55	2	5.1	11	56.1
Total				**€ 5,608.55**		
				€ 4,206,413	**per year (for 750 switches)**	

---

[1] Source: https://tradingeconomics.com/turkey/labour-costs

In total, it currently costs over €5,600 to assembly and install one switch. At the aggregate network level in Turkey, where on average 750 are installed every year, a total of €4.2 million is spent, using 750 installation shifts.

4.2.2 Do-Something scenarios

The DS scenarios have been defined also using the information gathered at the sites in Kayseri. Each DS scenario is the result of NeTIRail-INFRA researchers' observations and re-design of the existing processes currently applied in Kayseri, Turkey.

DS1: off-site assembly and transport to the site of a new switch, with lean techniques.

Application of lean principles to ensure that work is carried out correctly first time to the correct quality eliminating the need to correct previous work. This can be done with appropriate marking to ensure that correct joints are used, switch motor mountings were correctly installed prior to installation, over production does not occur with levelling the new ballast, and sleepers are correctly aligned as the switches are constructed beside the line. The precise details on how the process can become more efficient are explained in the technical deliverable D2.4

These improvements are expected to reduce the new switch installation time from the observed 6hrs 40mins to approximately 4hrs 30mins, saving two hours (based on the NeTIRail-INFRA researchers' observations and re-design as noted above). The equipment rental costs are expected to remain the same, however, this reduction of installation time would allow for two new switches to be installed in a single shift instead of 1, provided that the two switches are close to each other. For example, replacing two switches in the same station and work could be planned to ensure that such renewals are carried out in the same shift.

The line on which the observations were made had a very low volume of traffic. Therefore, in terms of reductions in possession time for this particular scenario, significant benefits in terms of increased capacity, fewer delays or cancellations are not expected. But, similarly, such benefits can be substantial for busy lines.

Finally, within this scenario the switch was already constructed and assembled in a previous shift, and these constructed parts were just installed during the observed shift on-site.

The table below summarises the information and costs of this scenario, in a way that is directly comparable with the DM scenario.

Table 4. Lean techniques for S&C: DS1 scenario information & costs

	Wage	Hours needed (per shift)	Cost (€,2017	Units needed	Total Cost
Switch unit cost	NA		5000	1	5000
Backhoe loader hire	NA		75	2	150
Installation shifts	28.05	9	252.45	0.5	126.225
Workers	2.55	9	22.95	11	252.45
Pre-assembly work	2.55	2	5.1	11	56.1
Total Cost per switch			**€ 5,332.33**		
Approximated Network Cost (750 switches)			**€ 3,999,244**		

Because of applying lean techniques, a total of almost €300 is saved per switch. This saving comes mainly from labour cost savings, being able to utilize each shift and to employ the 11 workers in a much more efficient way to install two switches per shift instead only one. That means, 99 hours of labour work are spared per switch, which translates into the €252.45 saving using Turkish average wages. Since the cost of the switch is likely to vary less than labour costs across countries, the overall impact of lean techniques will be much higher in countries where labour is more expensive.

At the network level, the lean process will save the Turkish railway approximately €200,000 per year. Additionally, in terms of track utilisation, the lean process will liberate 375 shifts in the network, equal to 3,375 hours per year, where the track could be used for other purposes (e.g. running services or conducting other maintenance work).

As a note of caution, it is acknowledged that the impacts of these lean techniques might be different for different locations. Since Kayseri is close to a station, its location is a factor that makes it feasible to do two switches instead of one. However, achieving such levels of efficiency might be more difficult in locations which are further away from a station due to logistical limitations. Hence, the approximated network cost of €3.99 million might be taken as an optimistic estimate. The total saving will depend on the location of each switch of the network, and the estimate of €5,332 per switch might only be achieved in those cases where the switches have relatively easy access.

DS2: S&C trackside assembly, with lean techniques

The second DS scenario considers the same improvements as above, but with the switch constructed on the lineside during the periods where the track workers were underutilised. For example, whilst the back-hoe loaders were being used to apply fresh ballast to the track and level it, the track workers were unable to work on track. It is estimated that this task which would normally take about 2 hours, could be carried out within the same 4hr 30min envelope of time, but using the underutilised track workers. This would save 2 hours of 11 workers time from what was previously categorised as “pre-assembly work”.

The following table summarises the information and costs for this scenario.

Table 5. Lean techniques for S&C: DS2 scenario information & costs

	Wage	Hours needed (per shift)	Cost (€,2017)	Units needed	Total Cost
Switch unit cost	NA		5000	1	5000
Backhoe loader hire	NA		75	2	150
Installation shifts	28.05	9	252.45	0.5	126.225
Workers	*2.55*	*9*	*22.95*	*11*	*252.45*
Pre-assembly work	2.55	0	0	11	0
Total Cost per switch			**€ 5,276.23**		
Approximated Network Cost (750 switches)			**€ 3,957,169**		

The second DS scenario represents a further push for efficiency compared to DS1. The difference is that the pre-assembly work will be spared. This is also estimated to need 11 workers and 2 hours (i.e. a total of 22 hours of labour per switch). In monetary terms, this means an additional saving of almost €50 per switch using Turkish average wages.

4.2.3 CBA outcomes

In this section we construct a CBA at the network level, using the information about DM and DS described above, for a time horizon of 30 years. The choice of time horizon is, in this case, not linked to asset life as it is not a relevant aspect of this evaluation. Any time horizon could have been chosen. The preliminary analysis from previous sections shows the main impacts of the innovation for one switch and for a one year at the network level. By choosing a 30-years horizon, we expand the analysis at the network level during this period of time, if the application of the lean techniques was perpetuated along 30 years. This analysis will thus provide an indication of the magnitude of the benefits of lean techniques for the Turkish railway if applied extensively across the network. The analysis at the network level is an exception within this deliverable, as normally we would choose to perform the analysis at the route/corridor level. However, for this specific case, we have reliable information of the total amount of switches installation performed yearly at the network level, but not so at the route level. It therefore seemed more informative to escalate the costs and benefits of lean techniques ‘at the site level’ to the ‘network level’.

Lean techniques are simply an organizational or managerial improvement, therefore it comes at no extra monetary cost to the railway. The benefits of two sets of lean techniques (as described by DS1 and DS2 scenarios) are proportional to labour costs, and can also vary depending on the location of the switch. Due to this variability, we build the CBA under two distinct set of assumptions:

a) only half of the sites will be able to get the full benefit of lean techniques;
b) all sites can implement lean techniques.

Alternative a) is perhaps more realistic in the short term, but it is useful to illustrate how large the benefits might be if logistical barriers were removed such that lean techniques for S&C could be applied more widely. The two tables below show the results under both set of assumptions (A and B).

Table 6. CBA of lean techniques (assumption A)

		Costs and Benefits	
		Lean techniques to S&C	
		Time horizon=30 years ; @3% discount	
		Type of analysis: network level (Turkey)	
		Details: lean techniques DS1	Details: lean techniques DS2
		Assumption A: lean techniques only applicable to half of the switches	
Investment Costs (by stakeholder)	Stakeholder		
Infrastructure Manager (IM)			
Lean techniques implementation	IM	€ -	€ -
Benefits (cost savings, by stakeholder)			
Switch unit cost	IM	€ -	€ -
Backhoe loader hire	IM	€ 1,305,707	€ 1,305,707
Installation shifts (9 hours, L=11)	IM	€ 1,098,753	€ 1,098,753
Pre-assembly DS2 (2 hours, L=11)	IM		€ 488,334
Total Benefits over time horizon		€ 2,404,460	€ 2,892,794.11
Summary indicators of impact			
Net Present Value		€ 2,404,460	€ 2,892,794.11
Additional non-quantified benefits			
Infrastructure Manager			
Increased track availability		187.5 shifts	187.5 shifts

Table 7. CBA of lean techniques (assumption B)

		Costs and Benefits	
		Lean techniques to S&C	
		Time horizon=30 years ; @3% discount	
		Type of analysis: network level (Turkey)	
		Details: lean techniques DS1	Details: lean techniques DS2
		Assumption B: lean techniques applied to all 750 yearly switches	
Investment Costs (by stakeholder)	Stakeholder		
Infrastructure Manager (IM)			
Lean techniques implementation	IM	€ -	€ -
Benefits (cost savings, by stakeholder)			
Switch unit cost	IM	€ -	€ -
Backhoe loader hire	IM	€ 2,611,414	2,611,414
Installation shifts (9 hours, L=11)	IM	€ 2,197,505	2,197,505
Pre-assembly DS2 (2 hours, L=11)	IM		976,669
Total Benefits over time horizon		**€ 4,808,919**	**€ 5,785,588.22**
Summary indicators of impact			
Net Present Value		**€ 4,808,919**	**€ 5,785,588.22**
Additional non-quantified benefits			
Infrastructure Manager			
Increased track availability		375 shifts	375 shifts

The Net Present Value (NPV) indicates that the total discounted benefit of using lean techniques, over 30 years in the whole network, can be between €2.4 million and €2.9 million under the assumption that only half of the switches can be installed with lean techniques. The €2.4 million figure corresponds to the DS scenario 1, where lean techniques allow the installation of two switches instead of one in the same shift. The assumption therefore is that this is possible for 375 switches, which would now require 187.5 shifts instead. The remaining 375 yearly switches continue to be installed using current practice. If, additionally, the switches were assembled on site using the same labour force during the installation shift, then the estimated benefits could reach the €2.9 million over 30 years.

Secondly, if it was feasible to implement these sets of lean techniques on all 750 switches, the total benefits in the 30-year period would range from €4.8 million to €5.8 million.

Additionally, there is an added benefit of track availability to the IM since the reduction in shifts means that the track can be available for other uses (e.g. other maintenance and renewal activities, or even train operations). We have not been able to obtain a realistic monetary value for track availability in Turkey, and hence it is more sensible to present this benefit in terms of shifts (where each shift is assumed to last 9 hours).

Summary

Lean techniques for S&C constitute an organizational improvement at no monetary cost that can bring substantial efficiency gains and cost savings to the railway. The NeTIRail-INFRA team would like to thank colleagues from TCDD and Intader in Turkey for giving us the opportunity to observe their processes from the replacement of a S&C. It was evident that they had good processes in place, and during the observations it was very clear that despite multiple activities going on in parallel the staff knew the tasks very well and communication worked extremely well within team. However, an outside perspective on the process allowed the identification of inefficiencies with this particular example. Consequently, the NeTIRail-INFRA team developed ideas, design changes and process changes which may have the potential to prevent some of the lean 'wastes'. The proposed changes are changes at the margins to existing processes and we therefore consider them to be realistic and feasible. Positive feedback was received from TCDD on the NeTIRail-INFRA report (D4.2).

In this section we have provided an economic assessment of several suggested design and process changes (i.e. lean techniques), which we have referred to as Do-Something scenarios 1 and 2. Furthermore, we have escalated the estimated benefits at the network level to give an indication of the full potential of lean techniques for S&C for the whole railway.

In summary, we have seen how a no-cost improvement can bring substantial cost savings through a more effective employment of workers and use of tracks. The total NPV at the network level can range from a conservative €2.4 million to €5.8 million depending on the assumptions made. These benefits are highly related to labour costs, and therefore are expected to be larger the higher the wages are.

4.3 CBA of the choice between different fastening systems

The way in which the fastening system (made of up clips and rail pads) functions may explain corrugation initiation. The engineering aim of this task is to provide a theoretical understanding of what causes (short pitch) corrugation. Identification of corrugation drivers opens the possibility to design the fastening system as well as tracks and sleepers in ways that reduce the need for maintenance.

The default approach for addressing the choice between different fastening systems is to compare a Do-Minimum scenario with a Do-Something scenario which includes the conclusions from the research provided within the scope of NeTIRail-INFRA and which assesses the life-cycle costs for track (re-) investment and maintenance for the respective scenario. At present, information about the link between the fastening system, corrugation and maintenance is not available. Information about maintenance costs for different fastening systems in the case-study countries is also missing. Instead, available information from another country, namely Sweden, is used to illustrate the type of analysis that could provide better understanding of the links between maintenance costs, the choice of fastening system design and the consequent choice of fastening system when tracks are to be renewed. A background paper including the full analysis of this material is attached as Appendix A.

4.3.1 Do-Minimum and Do-Something scenarios

Available information will not facilitate a “clean” analysis of a DS-scenario – doing something new to reduce the risk for corrugation – relative to the DM situation. Available information does, however, provide an indirect indication of the significance of the fastening system, the risk for corrugation and the need to act to eliminate rail-surface corrugation, i.e. to grind tracks. Specifically, since different types of fastenings are used in Sweden’s railway system, and since the type of clips used may affect the risk for corrugation and for track grinding, the analysis provides a comparison of maintenance costs for using the respective types of clips. Subsequently, “the fastening system” and “clips” will be used as synonyms.

The fastening system is, however, closely linked to the choice of sleepers in that wood, concrete and slab-track sleepers have their own specific fastening devices. Since corrugation is measured in Turkey on a line where concrete sleepers are used, this is the focus of the analysis.

Information about Swedish tracks includes all three sleeper categories, and it is not feasible to directly identify maintenance costs for different types of concrete-sleeper fastenings. As will be further described below, the analysis must therefore start by including all fastenings and sleeper types into the econometric analysis before the costs for maintaining different types of fastenings for concrete sleepers can be isolated.

The assessment compares annual maintenance costs for two existing fastening types used in the Swedish network. The Benefit-Cost test is therefore concerned with the benefits (cost savings) from switching from one type of fastening to another, relative to the extra cost of using the cost-saving option.

Wholesale, network-wide changes from one type of clip to another are, however, not made in practice. Instead, if it can be established that one type of clip has a lower annual maintenance cost than another, the transfer to the cheaper alternative is done at the same time as a scheduled track renewal. The cost to be included in the analysis is therefore the overall renewal package including both sleepers, rails and the costs for using two different designs of fastening system.

Since tracks will be used over many years, the choice between different designs has consequences for their whole life cycle. The DM and DS options are therefore considered in the following way: for both types of equipment, the expected life length is assumed to be 25 years:

Do Minimum: Investment cost for track renewal using clip C4. Annual maintenance costs for this clip.

Do Something: Investment cost for track renewal using clip C7. Annual maintenance costs for this clip.

The table below shows that C4 on average is used on many more track-meters than C7. The design of DM and DS is, however, based on that clip C7 is constructed in a way that makes it possible to fasten and released it with machines, while clip C4 requires manual work. Moreover, C7 is now the default option in Sweden at track renewal. However, we do not have information on the difference in track renewal cost between clip C4 and clip C7.

Table 8. Descriptive statistics, clips used on average track sections for concrete sleepers and slab track for the years 1999-2014 (3066 obs.)

		Track length on sections (meters)				*Share of track length on sections*			
Variable	Definition	Mean	St. dev.	Min	Max	Mean	St. dev.	Min	Max
	Concrete sleepers								
C1	"Fist clip", only used in Sweden	1 856	7 327	0	93 339	0.03	0.10	0.00	0.97
C2	Hambo clip, Swedish construction	5 492	17 285	0	174 230	0.09	0.20	0.00	0.99
C3	Base plates/Clamping plates	0	8	0	387	0.00	0.00	0.00	0.05
C4	E-clip, pandrol	34 473	43 991	0	232 570	0.47	0.38	0.00	1.00
C5	E-clip, deep-post, pandrol	2	117	0	6 459	0.00	0.00	0.00	0.04
C6	E-clip plus, pandrol	5	65	0	1 316	0.00	0.00	0.00	0.04
C7	Fast clip, pandrol	1 314	5 845	0	70 057	0.02	0.10	0.00	1.00
	Slab track								
S1	VIPA 5, for slabtrack (Pandrol)	0	3	0	184	0.00	0.00	0.00	0.00
S2	VIPA 6, for slabtrack (Pandrol)	0	2	0	132	0.00	0.00	0.00	0.00
S3	Pandrol VIPA F1	1	14	0	418	0.00	0.00	0.00	0.01
S4	Pandrol VIPA SP	1	22	0	902	0.00	0.00	0.00	0.01
S5	Vossloh Cogifer (for turnouts)	4	75	0	1 561	0.00	0.00	0.00	0.01

4.3.2 Cost and Benefits of the choice between fastening systems

The logic of the CBA analysis is as follows: The IM is about to renew x km of tracks. The question in focus of the present discussion concerns the choice of fastening system: If one system (one type of clip) generates lower maintenance costs over the life-cycle of the new tracks, this is one important determinant of the choice between different technical solutions.

If the reason for train disturbances that emanate from the infrastructure could be traced to the choice of fastening system, this could be relevant to include in the analysis. To establish this link, it is necessary to link train delays to (in our case) type C4 and type C7 clips. While this type of information is available, it has not been feasible to analyse these data within the scope of the present assignment.

Costs

Based on Swedish spending on track renewals from 2008 to 2014, the best estimate is that the average renewal cost is SEK 6 000 per track meter (price level 2014).[2] For the present purpose it is necessary to establish the difference in costs between a project using clip type C7 rather than type C4. This information is, however, currently not available. The average track meter cost will therefore be used as a benchmark in the concluding section.

Benefits; effect on maintenance costs

Information about the network has been collected from the Swedish Transport Administration (*Trafikverket*). This includes a lot of evidence about infrastructure characteristics and traffic. All maintenance activities are tendered by *Trafikverket* and implemented by contractors. When contractors invoice *Trafikverket*, costs are routinely allocated to each of the country's 220 track sections based on a recording system and on the bill of quantities for the different sections in the maintenance contracts. Information about maintenance costs are at the track section level for each year between 1999 and 2014.

The first row of Table 9 demonstrates that the average annual maintenance cost per track section is SEK 11.1 million. The next two rows provide information about traffic measured in two ways; train km and ton km. The remainder of the table summarizes some of the technical variables that is available for analysis. Since many different types of clips have been installed on the Swedish railway over the years, the network today comprises the clips is enumerated in Table 8.

The purpose of the econometric analysis is to establish the impact of the different explanatory variables on the annual track maintenance costs. The results of this analysis are reported in Table 10. The first two rows indicate that a 10 percent increase of traffic or in switch length would boost costs by 1 and 2.2 percent, respectively. Increasing the quality class would rather reduce maintenance costs; since quality classes runs from 1 (high) to 5 (low quality), this indicates that it costs less to maintain low-quality tracks, ceteris paribus. Whilst the relationship between cost and quality could take either sign, one explanation for the finding in this case could be that a quality class at 1 implies high speeds allowed and stricter requirements on track geometry standard, and vice versa for a quality class at 5.

---

[2] When this is written, the exchange rate is about SEK10/€1, meaning that dividing the Swedish numbers by 10 provides a proxy value expressed in Euro. This is per se irrelevant for the analysis which focuses on the balance between costs and benefits and seeks to establish a generic method for this exercise.

Table 9. Descriptive statistics of costs, traffic and infrastructure characteristics at the track section level at the Swedish railway network, 1999-2014

	Obs.	Mean	St. dev.	Min	Max
MaintC (2014 prices)	3 066	11 109 998	13 879 411	5910	209 217 288
Ttden (train-km/route-km)	3 066	17 102	21 342	0.2	192 475
TGTden (ton-km/route-km)	3 066	7 602 503	8 443 826	15.8	65 854 579
Track_l (meters)	3 066	70 211	54 936	1473	299 154
Rail_age (average age, years)	3 032	21	11	1	96
Rail_w (average weight, kg)	3 066	51	5	32	60
Qualave (average quality class; linespeed)	2 955	2	1	0	5
Switch_l (meters)	3 019	1 709	1 691	29	14 393
ConcSleep_l (track_l, meters)	3 066	43 328	49 489	0	281 124
WoodSleep (track_l, meters)	3 066	22 053	30 686	0	176 928
SlabSleep (track_l, meters)	3 066	5	89	0	2 050
Bridge_no.	3 066	26.3	30	0	224
Tunnel_no.	3 066	1.3	5	0	44
ReinfStruct_no.	3 066	0.03	0.38	0	9
D.Reinf_i	3 066	0.04	0.20	0	1
D.Struct_i	3 066	0.99	0.11	0	1
D.TimeD.ReinfStruct	3 066	0.01	0.10	0	1
ReinStruct_no._share	3 066	0.00	0.01	0	0.5
Ctend (dummy when tendered in competition)	3 066	0.47	0.50	0	1
Mixtend (dummy when mix between tendered and not tendered)	3 066	0.06	0.24	0	1

Table 10. The impact on costs of traffic and technical variables. Model 1 (baseline=clips for wooden sleepers), Fixed effects (2912 obs.)

	Coef.	Rob. Std. Err.
Cons.	13.12067***	0.753939
ln(Tgtden)	0.0985**	0.0388
ln(Switch_l)	0.2254***	0.0587
ln(Qualave)	-0.4665***	0.1635
Clip C1_share of track_l	-0.4168*	0.2410
Clip C2_share of track_l	-0.1174	0.2843
Clip C3_share of track_l	-29.0508***	2.5250
Clip C4_share of track_l	-0.3558***	0.0971
Clip C5_share of track_l	10.8794	7.3239
Clip C6_share of track_l	3.7194	2.4170
Clip C7 _share of track_l	-0.8951***	0.2242
Clips S1-S4_share of track_l	62.2951**	26.7930
Clip S5_share of track_l	25.4163***	3.5026
Clip U1_share of track_l	-0.2124	0.2829
Mixtend	-0.0124	0.0398
Ctend	-0.1351***	0.0451
Year dummies 2000-2014[a]	Yes	

***, **, *: Significance at 1%, 5%, 10% level, [a] Jointly significant (F(1, 215)=19.27, Prob>F = 0.000).

The prime interest here is, however, the consequences for maintenance costs from using different types of clips. The immediate observations that can be made from the Table 10 results relates to the cost impact of switching from wooden sleepers (with its average clip type; this being the baseline for comparison) to concrete sleepers with the respective clip types. Assume, as a thought experiment, that the share of clip C7 would increase from the current (about) two to four percent of the (average) track section length. This implies that costs would fall by[3] $(100 \cdot [\exp(-0.8951 \cdot 0.02) - 1] = -1.774)$ about 1.8 percent compared to using the average wooden sleepers. If we instead make the corresponding switch to clip C4, the coefficient value -0.3558 would be inserted in the expression, indicating that maintenance cost would be reduced by 0.7 per cent.

This result can also be used for understanding the consequences of a switch from C4 to C7 clips on concrete sleepers. In that case, the annual maintenance costs would shrink by (1.77-0.7=) 1.07 per cent; the difference between clip-coefficients is statistically significant (F(1, 215)=5.26, Prob>0.023). Since the average maintenance cost on a track section is SEK 11.55 million (based on the estimation sample), this corresponds to an annual saving of SEK 123 089. This is the result that will be used in the subsequent summary of results.

This analysis has established the direct impact on maintenance costs by switching from one fastening system to another. While the result is statistically robust, it does not have much to say about which activities are affected. We do, however, have information also about the extent of track grinding each year. Since grinding is a means for reducing track corrugation, and since the need for grinding may be

---

[3] The generic expression is Using ΔC/C=100·[exp(β ̂_k ΔX_k)-1], where β ̂_k is the parameter estimate for variable X_k, gives us the percentage change (Δ) of the predicted maintenance costs (C) when variable X_k changes.

related to which type of fastening system that is used, this provides complementary intuition about the effect of a change of investment.

Running a so-called corner solution model (see Appendix A), the (significant) coefficient indicates that clip C7 implies more grinding of rails compared to clips for wooden sleepers. Increasing the share of clip C7 from 2 per cent of the average track section length to 4 percent implies a 2.37 per cent increase in grinded track meters. This can be compared to the C4 clip where the corresponding switch from wooden sleepers would imply a 0.64 per cent increase.

However, it was previously demonstrated that this would still result in higher maintenance costs (about SEK 123 089 according to the model 1a results) when C4 is used compared to C7. This shows that it is important to consider more than one maintenance activity when comparing different fastening systems with respect to their impact on maintenance.

Summary

The engineering aim of this NeTIRail-INFRA task is to provide a theoretical understanding of what causes (short pitch) corrugation. In this way it would become possible to identify corrugation drivers and subsequently to design the fastening system as well as tracks and sleepers in ways that reduce the need for maintenance. Since information about the link between corrugation, the fastening system, and maintenance is not available in the case study countries, information from Sweden has been used to illustrate the type of analysis that could provide better understanding of the benefits of technical improvements. Importantly, new information has been revealed from the econometric model concerning the cost implications of using different clip types.

The illustrative example has come to establish that the use of C7 rather than C4 clips would reduce annual maintenance costs by SEK 123 000 (€12 300). At a discount rate of 3 per cent and over 25 years (based on the life of the asset) this corresponds to SEK 2.1 million (€210 000). Table 9 established that the average track section is 70 211 m long. The calculation made above considers a change of clips at 2 per cent of the average track section length, meaning that the annual saving would be (123 000/1 404=) SEK 87.59 (€8.76) or – over 25 years – SEK 1525 (€153) per meter.

The renewal cost is SEK 6 000 per meter on average. While the actual difference between renewal costs for clip C7 rather than C4 is not known, the present value of all future cost savings puts a cap on the extra cost for the change (of clip) to be motivated; the difference could not be larger than SEK 1 526 (€153), corresponding to 25.4 per cent of the average track renewal cost. The example illustrates the logic that technical development must meet in order to result in performance improving – in this case cost reducing – changes: If better understanding of the forces behind track corrugation would facilitate the use of a fastening system that requires less maintenance, there would be a business case as well as an overall economic case for the change, given that the savings are of a certain magnitude.

4.4 CBA of lubrication techniques

An efficient lubrication of the wheel-rail interface can reduce rail and wheel wear as well as energy consumption, leading to substantial cost savings (Reddy et al., 2007). Quoting NeTIRail-INFRA Deliverable D2.7, “correct and proper management of the rail–wheel interface helps the rail industry to reduce wear and fatigue, which results in enhancement of asset life, growing of rail industry’s business and improving reliability of service. In the case of railway curves, properly and efficiently applied lubricants decreases squeal on corners and reduce rail noise. Similarly, correctly applied lubricants can reduce wear on track and wheel, particularly on the contact zone on the outside curve”.

The background to this task derives from technical limitations of a pumping system in use in Turkey. While this challenge has now been solved, the development of solutions has – except for providing some quantitative evidence – resulted in testing of further innovations. Several issues have been addressed as part of the NeTIRail-INFRA project: when, how and how much lubrication should be used? Which type of lubricant? Is it best to use a track based or an on-vehicle system?

In this section, we provide a cost-benefit analysis framework for the economic appraisal of a lubrication system, and illustrate this for an on-board lubrication system implemented in Slovenia. The framework is generic whereas the numerical example is specific to one case study line.

To evaluate the economic impact of a lubrication system, it is necessary to decide what is the baseline (or Do-Minimum scenario). One option is to compare it against another (already implemented) lubrication system. Alternatively, it can also be compared against a situation in which no lubrication is implemented. For our case study, we have selected the latter option and defined the DM and Do-Something (DS) scenarios as follows:

- DM: no lubrication
- DS1: on-board lubrication

The information about all scenarios have been gathered through discussions with experts in the industry, in particular in the context of the Slovenian railway, as well as from existing studies. The framework can easily be extended to appraise any other lubrication system (e.g. a track-side lubricant), provided that all impacts are identified and monetary valuations are available for them.

4.4.1 Do-Minimum Scenario

The DM scenario is defined as the operation and maintenance of the railway (or one specific line) without the use of any lubrication system. Existing evidence shows that wear has a detrimental effect on rail and wheel life, adding to both maintenance and renewal costs (Reddy et al., 2007). Rail and wheel defects, breaks and derailments are costly for the rail industry each year due to the need for maintenance operations, track possessions, cancelled and delayed traffic, emergency maintenance, loss of assets, loss of revenue etc.

However, lubrication systems can also be costly. While for many railways across the world lubrication is a standard practice, low density lines may struggle to make a case to pay for and implement a lubrication system, and detailed economic analyses are necessary. The aim of this task is to illustrate a cost-benefit analysis for a lubrication system that could be useful for Infrastructure

Mangers (IM) interested in a full economic understanding of a potential investment in this maintenance technology.

While lubrication work is not really new, the technical work in NeTIRail for this aspect of the railway has been about selecting the most appropriate lubrication for the correct conditions and locations. Ideally, we would have liked to assess the newly tested lubrication system against another currently used lubrication system. However, the available data did not support this comparison. Instead, we compare the costs and benefits of implementing the tested lubrication system against a scenario where no lubrication is implemented. Thus, we show the maximum economic potential of the tested lubrication system against a 'do-nothing' scenario. The information could then be compared independently against other lubrication systems if suitable data and a comparable CBA were available. The CBA framework we provide is also easily replicable for other case studies and lubrication systems.

The information on costs and benefits was expected to be provided by partners from WP2. Most of the information came from experts in the case study country (Slovenia), and thus this is the main data source for the analysis. Additionally, some parameters and unit costs were obtained from existing studies.

The line/s used for this case study are from Slovenia. The following table summarises their characteristics. The focus is placed on the freight route line Divača – Koper, with a track length of 48 kilometres. This line is particularly important for international rail freight traffic, given the role of the Port of Koper in linking the Slovenian hinterland with the European economy.

Table 11. Slovenian case study lines

Category	Slovenia
Busy, capacity-limited passenger railway	Ljubljana – Kamnik 23.6 km ST, diesel 10 276 PT – 0.4 MP 506 FT – 0.08 Mt
Under-utilised secondary line	Pivka – Ilirska Bistrica 24.5 km ST, 3 kV = 4 141 PT – 0.02 MP 1 451 FT – 0.57 Mt
Freight dominated route	Divača – Koper 48.0 km ST, 3 kV = 4 420 PT* – 0.1 MP 20 837 FT – 11.04 Mt

Elements that can be influenced by lubrication

To define the DM scenario, it is useful to be specific about what elements of the overall railway system are affected using effective lubrication techniques. Following discussions with engineers and experts as part of the NeTIRail-INFRA project, the following elements are identified:

- Life of wheels and rail
- Frequency of other maintenance tasks, mainly grinding

- Fuel consumption
- Track availability
- Safety

Other studies (e.g. Reddy et al., 2007) also identify inspection costs as an element that can be influenced by lubrication. However, this effect is likely to be very minor, since tracks and wheels are likely to be inspected almost as much even if lubrication is in place, due to the multiple types of damage that they can suffer and to ensure safety regulations are met.

The following table summarises the main information of the DM scenario which is relevant for the cost-benefit analysis:

Table 12. Description of Do-Minimum scenario (no lubrication)

	DM (no lubrication)	
Wheels		
	Km driven	**Years**
Life cycle (km & years)	500000	4
	Shifts/life cycle	**Days of absence/shift**
Grinding (shifts & absence time/shift)	12	1.5
Replacement (shifts & absence time/shift)	1	12
	Cost	
Grinding shift (wheels of 1 locomotive)	€ 300.00	
Replcament (wheels of 1 locomotive)	€ 13,000.00	
Cost of locomotive absence (per day)	€ 2,000.00	
Fuel consumption (€ per km)	€ 1.40	
Rail track	**Years**	
Life cycle (years)	25	
	Cost	**N of shifts for 48km**
Track grinding, cost in €/km	€ 4,500.00	
Track grinding full line (48km), every 3 years	€ 216,000.00	4

The central figures for the analysis are at the top of the table. If the wheels are not lubricated, we shall expect a life cycle of 4 years, where the wheels would need grinding up to 12 times in that period. In those conditions (no lubrication), the track would be expected to last approximately 25 years.

Most of the information was obtained directly through conversations with rail experts in Slovenia as part of the NeTIRail-INFRA project, with the following exceptions. The information about fuel costs is obtained through an international study, which shows that fuel costs are relatively similar across European countries (Beck et al., 2013), ranging somewhat between 1 and 1.8 EUR/train-km. We assume an average of 1.4 EUR/km. The figure for average track grinding cost is approximated based on a US research project which developed a comprehensive model for the costs of grinding, also validated by industry partners. However, the unit cost of grinding varies significantly between IMs, passenger/freight transport and countries. The chosen figure of €4,500 is closer to the lower end of the estimated range (relating to relevant freight transport values).

4.4.2 Do-Something scenarios

The DS scenario is defined as the operation and maintenance of a rail line with the implementation of an on-board lubrication system, tested in Slovenia. On-board lubrication is a method where the lubricator is mounted on the locomotive, and the lubricant is applied to the locomotive wheel flange.

In Slovenia, both on-track and on-board lubrication systems are used by SZ (Slovenian Railways). With respect to on-board lubrication, SŽ has been using products from ELPA, SIEMENS, ANSALDO, SAB WABCO, REPSO, TVT, SKF. The lubrication of the wheel flanges reduces the friction in the arc and thereby extend the life of wheels and rails. Locomotives, shunting locomotives, electromotive train set, diesel motorized train sets of SZ are the vehicles which have on-board lubrication systems whereas wagons are not lubricated. With respect to the type of lubricant, SZ has been using oils and grease.

From previous experiences with other on-board lubrication systems in Turkey, TCCD has reported that the benefits of these systems can include:

- Increased rail and Wheel life due to reduced wear
- Reduced derailment due to increased safety
- Reduced fuel consumption between 5-10%
- Reduced workmanship as result of avoiding bogie welding
- Reduced material cost due to avoiding bogie welding
- Increased wheel life
- Reduction in other defects arising from installing and removing the wheels from wagons and locomotives

Investment costs of on-board lubrication

The first step to assess the economic case of a lubrication system is to understand its costs. Different lubrication systems have different implementation costs. In Slovenia, there are currently different types of lubricants used, through different providers.

We will focus on the lubricant that is in testing phase (SINTONO TERRA SK), which has a cost of approximately 20€/kg. Other types of soft grease lubricants used in Slovenia (e.g. CICO 1500 TL or TRAMLUB) have a very similar cost per kg. The lubricating device has a capacity for 18 kg.

Currently, we can estimate the cost per train-km only using information of the freight fleet in Slovenia. The total driven km is 165,000 km/year for the whole fleet of 70 locomotives (32x ELOK 541 and 38x ELOK 363). This means that approximately, 2,400 km/year are driven by one locomotive. Each locomotive undertakes an average of 10 reviews per year to refill the system with the lubricant, and each review adds an average of 11.5 kg (these figures vary by locomotive type, but not excessively and therefore it seems adequate to use an average). At the average cost of 20 €/kg, one locomotive would incur a lubricant cost of approximately €2,300 (for 115 kg) per year. For the 2,400 km driven, these numbers would imply a cost of 0.96 €/km for one locomotive.

Additionally, there is a cost of maintaining the lubricating system. This cost is approximately €60,000 for the whole audit period (about 6 years) for the whole fleet of 70 locomotives. This includes cost of inspection, assembly, disassembly, replacement of spare parts, without cost of the lubricant (described earlier). If we divide this €60,000 figure by the number of year it refers to (6 years) and the number of locomotives (70), we get an approximate average annual cost of €143 per locomotive.

Of course, for this figure to be relevant for use, the system needs to be implemented widely in a network (such as it is the case in the freight Slovenian fleet) and not only on one locomotive.

The investment costs information is summarised below together with the rest of the relevant information for the DS scenario.

Impacts and costs of on-board lubrication

The following table summarises the key information to build up the DS scenario, e.g. data on how much the wheel and rail life extends with the applied on-board lubrication, maintenance reductions, and so on. It is presented in a way that can be directly contrasted with the DM scenario information provided above.

Table 13. Impacts and Costs of on-board lubrication

	DS (on-vehicle lubrication)	
Wheels		
	Km driven	**Years**
Life cycle (km & years)	750000	6
	Shifts/life cycle	**Days of absence/shift**
Grinding (shifts & absence time/shift)	10	1.5
Replacement (shifts & absence time/shift)	1	12
	Cost	
Grinding shift (wheels of 1 locomotive)	€ 300.00	
Replcament (wheels of 1 locomotive)	€ 13,000.00	
Cost of locomotive absence (per day)	€ 2,000.00	
Fuel consumption (€ per km)	€ 1.26	
Rail track	**Years**	
Life cycle (years)	30	
	Cost	**N of shifts for 48km**
Track grinding, cost in €/km	€ 4,275.00	
Track grinding full line (48km), every 3 years	€ 205,200.00	
Lubrication system	Kg/review	Reviews/year
Consumption (quantities for 1 locomotive)	11.50	10
	Average Kg/year	
Consumption (1 locomotive)	115	
	Cost	
Yearly Inspection, (dis)/assembly, replacement of parts	€ 143.00	
Lubricant (€/kg)	€ 20.00	
Total Lubrication cost (1 locomotive/year)	€ 2,443.00	

As in the case of the DM scenario, most of the information comes from discussion with experts in freight railway in Slovenia, together with additional inputs of experts from Turkey. If lubrication is used, the wheel life is expected to increase to 6 years instead of 4. At the same time, during this longer time span, only 10 grinding shifts are needed (instead of 12 in 4 years); this is probably the main direct impact of lubrication. Additionally, TCDD in Turkey has evidence of fuel consumption savings. Based on their experience with a rail-wheel flange lubrication system (a system that lubricates between rail head and wheel and between the wheels of wagons and bogie), while reducing the rail and wheel wear through lubrication, it is also seen that the fuel consumption is reduced by 5%-15%. Interestingly, their evidence on wheel life extension is also 50-55%, which is very similar to the estimates provided by Slovenian experts.

With respect to the effect of the lubricant on the track, it has been seen in Turkey that the rail life increased 45% on alignments and 150% on curves. In Slovenia, however, experts suggest that rail overhaul occurs every 30 years rather than every 25 years when a lubrication system is in place. On the other hand, an existing study on the impacts of lubrication in Australia (Reddy et al., 2007) suggests a 5% reduction in grinding costs thanks to the use of lubrication. We have applied this figure to the estimated costs of grinding. However, the impact of grinding is difficult to be perceived at the route level, but it would certainly have an impact at the network level if, e.g., the use of lubrication allows to reduce the number of grinding shifts such that one grinder can be spared.

4.4.3 CBA outcomes

The implementation of the on-board lubrication system has benefits for both the wheels and the rail track. The following table (14) summarises the results of the CBA of the implementation of lubrication in one freight route in Slovenia. The time horizon corresponds to the higher life of rail in the DS scenario: 30 years.

The implementation of this on-board lubrication system for one locomotive in the selected freight line costs €2,443 per year (in €2017, not discounted). For the 30-year period and using a 3% discount rate, this translates into a total cost of €56,708. This means that, approximately, for it to be worthwhile in an economic sense, it should generate discounted benefits equal to at least €1,890 per year on average. Given the existing evidence on benefits from lubrication systems, it seems highly likely that such benefits can be achieved as suggested by the benefits indicated in Table 14.

Table 14 shows all identified benefits, monetized and non-monetized. The NPV and BCR are calculated at the route level, but crucially only include the monetized benefits. Non-monetized benefits should therefore be treated as additional. The NPV is approximately €208,000, indicating a net positive benefit from the implementation of lubrication. The quantified benefits come from life cycle cost savings (approx. €120,000) and increased availability of the locomotive due to reduced maintenance and renewals of the wheels (approximately valued at €144,000; this figure is based on an estimate of €2,000 opportunity cost per day[4] of locomotive absence, and an estimate of the number of absence days that would be saved; see tables 12 and 13 above). Dividing the total benefits by the total costs of the project we obtain a Benefit-Cost Ratio (BCR) of 4.68, which can be regarded as high value for money (DfT, 2017). Given that all other non-monetized effects are positive, these figures can be regarded as the low bound of the total economic impact of the project.

A clear-cut benefit that has not been monetized is the 5 extra years of life for the rail track. This could be calculated with information about the cost of rail in Slovenia. Furthermore, the use of lubrication, through improved maintenance, has the potential to reduce number of failures.

---

[4] The €2,000 figure was provided by a rail expert in Slovenia and can be related to revenue lost and the additional costs of replacement.

Table 14. CBA output table for the on-board lubrication system

		Costs and Benefits
		Lubrication
		Time horizon=30 years ; @3% discount
		Type of analysis: line specific (Divača – Koper; Slovenia):
		Details: one freight locomotive with on-board lubrication system
Investment Costs (by stakeholder)	Stakeholder	
Infrastructure Manager (IM)/Train Operator (TO)		
Lubrication system fixed costs	IM/TO	-€ 3,319
Lubricant	IM/TO	-€ 53,389
Total Costs over time horizon		**-€ 56,708**
Average annual cost		-€ 1,890
Benefits (by stakeholder)		
Wheels replacement	TO	€ 27,906
Wheels grinding (yearly)	TO	€ 9,285
Track grinding (yearly)	IM	€ 83,565
Life cycle cost savings from M&R		€ 120,756
Locomotive absence (replacement)	TO	€ 51,518
Locomotive absence (grinding, yearly)	TO	€ 92,850
Benefits from reduced locom. Absence		€ 144,369
Total Benefits over time horizon		**€ 265,125**
Non-quantified Benefits		
Infrastructure Manager		
Increased rail life		Residual value of 5 years
Rail users		
Delay reductions		(+)
Safety risk reductions		(+)
Other Benefits (N/A for this line)		
Train Operator		
Reduced fuel consumption		10% reduction (0.14€/km)
Summary indicators of impact		
Net Present Value		€ 208,416
BCR		4.68

Reducing number of failures would lead to reduced delays and increased safety, which can be regarded as additional benefits for the users of the line. Unfortunately, no data about the current number of incidents and delays is available, and therefore it is not possible to provide a detailed quantification.

Importantly, the case study line is electrified and therefore the fuel consumption savings have not been incorporated. Otherwise, fuel savings would be an added benefit from lubrication in non-electrified lines. For example, as an illustration, for a locomotive driving 10,000 km/year, the fuel savings are expected to be approximately €1,400 per year.

Summary

The economic analysis of lubrication techniques shows that this technology can offer substantial benefits to all agents in the rail industry (IMs, operators and users), at a relatively low-cost. As part of the NeTIRail-INFRA project, an on-board lubrication system has been tested in Slovenia. While many different lubrication systems exist, their understanding in economic terms is limited. The Australian study reported in Reddy et al. (2007) is a good example of how robust economic analysis can help to shed light on the benefits of lubrication systems, but the evidence is overall scarce (see Deliverable D2.7 for a general overview of lubrication studies).

In this section, we demonstrate for a case study in Slovenia that the tested on-board lubrication system can generate significant cost savings in the maintenance of both wheels and rail. Life extension of both wheels and rail further contributes to more cost savings. Additionally, rail users could benefit from a network with less failure-caused delays and accidents. Overall, our analysis suggest that this lubrication system is high value for money.

To finalise, a short note of caution. While the analysis has been performed at the route level as an illustration, we expect the full benefits of a lubrication system to materialize only if a larger scale implementation is performed (e.g. for a group of routes or at the network level). If that is the case, for train operators, the fixed service costs of the lubrication systems (i.e. excluding the lubricant) can then be split across routes, as we have assumed in our analysis. Also, for the IM, if several locomotives cover a given route, the benefits on the track probably require that more than one locomotive is equipped with the technology.

Future case study in Turkey

The proposed CBA framework is easily replicable and adaptable to the study of other lubrication systems. For instance, we are aware that Turkey is currently testing a new technology. When data becomes available, TCDD can use this framework in Turkey to assess their newly tested lubrication system: On-Board Solid Stick Lubrication. After many experiments with diverse results during the last two or three decades, in 2016, TCDD has started to use solid sticks for lubrication. These systems do not require a significant maintenance and workmanship, and it is easy to use. It has been mounted on two locos "DE 36000" of TCDD. At the time of writing the system is in test phase. The feedback so far is that performance is satisfactory on wear, and the system is easy to use and maintain. One of the objectives of this analysis has been to make it general, comprehensive and clear enough so that it can be used by any interested stakeholder.

4.5 CBA of heavier sleepers for transition zones

A transition zone is the section of tracks between the railway line and a bridge or tunnel. Maintenance of transition zones is more expensive than on plain lines, and existing transition zones technology does not help to make the rail components last long enough.

The purpose of task 2.6 is to reduce displacement that occurs in these zones, meaning that the NeTIRail-INFRA innovation for transition zones is concerned with changing the design features of transition zones. This could relate to the position, shape and mass of sleepers. The economic analysis is therefore concerned with comparing the costs of two ways to handle transition zones; a Do-Minimum meaning that the current spending on maintenance continues and a Do-Something scenario for the upgrading of the transition zone and the subsequent maintenance costs. Relevant information about the respective alternatives is missing and, again, information from Sweden is used to illustrate the type of analysis that can be implemented to provide an understanding of the trade-offs involved. Appendix A presents the full economic analysis.

4.5.1 Do-Minimum and Do-Something scenarios

The structure of the comparison is straightforward: Information about track maintenance costs per average track section is available for a sequence of years. Each track section has on average 26.3 bridges and 1.3 tunnels (cf. Table 9 in section 4.3), i.e. 28 structures with one transition zone at each end. Once again using econometric analysis, access to this information makes it possible to identify the cost consequences of reinforcing a transition zone at one or both ends of the structures.

The investment cost of the innovation

The technical research in this task is concerned with providing a better understanding of why transition zones are costlier to maintain than the straight line. The ultimate purpose is to use this information to establish more precisely how the zone design could be improved to reduce costs. This second issue has, however, not been addressed. No information about the costs for the strengthening of transition zones is therefore available.

The benefits of transition zone improvement

The information displayed in Table 9 above can be used also for estimating the costs for transition zone maintenance. Table 15 summarizes the econometric evidence of what explains variations in track maintenance costs.[5] The impact on costs of traffic and switch length (the first two rows) has the expected sign – i.e. more traffic and increasing the number of switches increases maintenance – and are statistically significant.

The parameter estimate for the number of bridges and tunnels (Struct_no.) is 0.1667 and statistically significant at the 5 per cent level. The estimate can be interpreted as an elasticity due to the double log-specification of the model. This means that increasing the number of structures on an average track section with 10 per cent would increase the maintenance costs with about 1.7 percent.

The average maintenance cost in the estimation sample is SEK 11.38 million per track section and there are 28.3 structures per section in the sample. This means that a 10 per cent increase implies

---

[5] We considered using the same model for the two econometric analyses (see Table 10). However, that would mean losing 101 observations. However, we do not consider that there is omitted variable bias by using a model that excludes the variables in Table 10 (partly because we used fixed effects and also based on further testing).

2.83 new structures on the average track section, and the estimated annual cost increase per structure is about (0.017*11 380 000/2.83=) SEK 68 400 or SEK 34 200 per transition zone.

This estimate is based on the overall costs for structures. Since not only the transition zone, but also other parts of the structures may require maintenance, this number provides an upper limit for the impact on costs if the number of transition zones would change.

Table 15. The impact on maintenance costs of traffic and technical variables. Model 3, Fixed effects (2978 obs.)

	Coef.	Rob. Std. Err.
Cons.	11.0436***	0.9720
ln(Tgtden)	0.1423***	0.0458
ln(Switch_l)	0.2393***	0.0877
ln(Struct_no)	0.1667**	0.0761
Reinstruct_no_share	-0.1581	0.3057
Woodsleep_share	0.3875***	0.0953
Slabsleep_share	27.9601***	6.2962
Mixtend	0.0144	0.0390
Ctend	-0.1034**	0.0511
Year dummies 2000-2014[a]	Yes	

***, **, *: Significance at 1%, 5%, 10% level,

[a] Jointly significant (F(15, 218)=17.05, Prob>F=0.000)

Table 15 also includes a variable for the share of structures that have reinforced transition zones (Reinstruct_no_share). This brings us a bit closer to our target since it makes it possible to estimate the consequences of transition zone reinforcement directly.

The coefficient has the expected (negative) sign, indicating that transition zone reinforcement reduces maintenance costs. The estimate is unfortunately not statistically significant (p-value is 0.606)[6], but we still use the same type of equation as above for estimating the cost impact of strengthening a transition zone. In this way, it is possible to illustrate the benefits of econometric analysis also on this detailed level, i.e. when a very specific activity (reinforcing the zone) is considered. Since we expect to get access to information about costs, traffic and technical characteristics of the network for another two years, and since transition zones seems to be gradually reinforced, it will be straightforward to update results (and we may expect increased statistical significance with more data).

The generic expression is $100 \cdot [\exp(\hat{\beta}_k \Delta X_k) - 1]$, where $\hat{\beta}_k$ is the parameter estimate for variable X_k (i.e. share of structures that are reinforced, where one structure corresponds to two reinforced transition zones). In this case, our thought experiment means that all structures will have their

---

[6] Note that only about 1.1 per cent of all the observations in the regression have a reinforced transition zone.

transition zones reinforced. Considering that there are on average 28.25 structures per section in the estimation sample that does not have reinforced transition zones, our thought experiment then corresponds to an increase of – an investment in – (28.25*2=) 56.5 reinforced transition zones.

Since the average share of structures with reinforced transition zones (variable used in the model estimation) currently is 0.063 per cent per section, the strengthening implies that the average value for the share of structures with reinforced zones increases from 0.00063 to 1 (i.e. with 0.9994). Using the estimated parameter implies a maintenance cost reduction with $(100 \cdot [\exp(-0.1581 \cdot 0.994) - 1] =)$ 14.6 per cent. Since the average maintenance cost per track section is SEK 11.38 million, this reduction corresponds to SEK 1.66 million per year and about SEK 29 400 per transition zone and year.

This result is close to the cost per transition zone (SEK 34 200) established above, indicating that the driving force behind structures being costlier to maintain than the straight line indeed seems to be the transition zones. “Seems” here refers to that the coefficient is not statistically significant.

Summary

Maintenance of transition zones is more expensive than on plain lines, and the ultimate purpose of task 2.6 is to identify the forces that drive the degradation and ultimately to change the design features of transition zones. This could relate to the position, shape and mass of sleepers.

Since information that would facilitate a comprehensive analysis of different ways to strengthen the zones is not available, the economic analysis has estimated cost savings from reducing or eliminating the extra maintenance cost. The maximum annual cost saving is SEK 34 200 (€3 420) for transition zone, i.e. SEK 68 400 (€6 840) per bridge or tunnel. It has also been feasible to derive a cost saving for structures where transition zones have been strengthened.

This reduction in costs lasts equally long as the transition zone itself. This is, again, a number that is not available. It is therefore assumed that the installation will be in place during 25 years before it must be replaced again. This means that the total saving can be translated to a present value of SEK 595 530 (€59 953). for each transition zone at a discount rate of 3 per cent. If the transition zone could be upgraded at this cost or less, it would be motivated.

To the extent that transition zone failures are sudden, i.e. irregularities are not detected so early so that preventive maintenance can be implemented, they may trigger train delays or even derailments. At the present stage, information about the frequency of this source of train delays is not available and can therefore not be incorporated in the quantitative assessment.

5. Cost-Benefit Analysis of WP3 innovations

WP3 contains five tasks. Task 3.1 introduces the existing overhead-line installations. This is followed by task 3.2 which discusses what influences performance. Tasks 3.3 and 3.4 present the innovations, although most of it comes together within task 3.4. Finally, task 3.5 is focused on some further testing.

The overall goal of the innovations of WP3 is to enhance the life-length and reduce costs of existing and future overhead lines. Three innovations are identified:

- Trolley wire model: an alternative design of overhead wires when new lines are considered for electrification.
- Optimised wire tension: means for making existing overhead lines more reliable. Specifically, changing wire tension is considered. This could be an adjustment that generates no or low up-front investment costs but that may lead to savings in maintenance cost.
- On-board monitoring of the overhead line: to collect electrical properties data in real time to optimise the maintenance plan.

5.1 Costs of Overhead line systems – literature review

The cost of railway electrification is directly linked to the design of the Overhead line system. This is driven by a number of external factors, such as

- speed of the line
- frequency of trains
- if freight trains will use diesel or electricity for traction
- type of rolling stock
- number of lines
- gradients
- underlying ground conditions
- lineside infrastructure issues, e.g., tunnels, bridges, structure clearance
- airborne pollution
- proximity to the sea

WP3 considers alternative designs of the overhead line system which are generic and can be useful for a wide variety of external factors. Competition between suppliers of equipment and the volatility of raw material costs has led to a reluctance for companies to quote budget prices without a specific application being known. It is therefore difficult to obtain precise cost data of different designs of overhead line systems for the case studies of Netirail. However, the literature has documented some estimates of electrification costs elsewhere. This section presents a state-of-the-art review of the costs associated with different overhead line models.

5.1.1 Traditional overhead line system

In general, the conducting wires, insulators and supporting structures installed along a railway line are collectively referred to as the Overhead line (OLE) system. The typical span of the OLE system (the catenary wire model) was shown by Figure 1. A more detailed illustration is presented in Figure 7 (adopted from Kilsby et al., 2016) to show the alignment of the major components of the OLE, including masts, catenary wire, contact wire, and droppers. Masts (sometimes also known as structures) support all OLE components by raising them above the track. Registration equipment is attached to the masts via insulators that separate the live components from Earth. The contact and catenary wires are attached to, and aligned by, the registration equipment and the contact wire is suspended below the catenary wire by droppers. The train's pantograph rubs against the contact wire to obtain the traction power. These components exist at each mast and repeat along the entirety of an electrified line. Since the span between masts is typically about 60m, the total number of OLE components on a line is considerably large.

Figure 7. Major components in the catenary wire model

Capital costs

Network Rail investigated the factors influencing the capital cost of electrification and the maintenance cost of fixed equipment and summarized in the report "Network RUS: Electrification Strategy (2009)". Capital expenditures usually occur during the initial year of the project when the OLE equipment is installed and are assumed not to incur costs in subsequent years. The installation costs are driven by two elements: the scope of electrification works required and the efficient use of construction resources. The former element depends on a number of factors, including the provision and installation of lineside equipment (overhead or third rail), gauge clearance works, provision of appropriate grid connections, distribution and supervisory control systems, signalling immunization works, track enabling works and other minor works. The latter element, efficient deployment of construction resources, requires usage of skilled installation teams, the acquisition of plant and the implementation of effective logistic arrangements such as depots and material supply.

In general, electrification unit rates can differ significantly by route dependent upon the characteristics of that route. Estimating the capital expenditures of the OLE system is challenging as it consists of many sub-systems and involves numerous components. With reference to various literature sources, we summarise the capital cost estimates of different railway electrification projects in

Table 16.

Table 16. Estimated capital expenditure of electrification

Beneficiary	Country	Section	Length (km)	Estimation year	Estimated cost	Inclusion	Reference
SNCF	France	Biliothéque François-Mitterrand and Brétigny (Essonne)	180	2017	€227 million	Installation of 2000 masts and 540km of cable	Barrow (2017)
Network Rail	UK	Great Western Main Line (GWML)	190.8	2009	£625 million	Including installation of electrification equipment, route clearance, programme management, signals and communications equipment, lead design organisation, risk and opportunity	Clark (2015)
				2014	£1.7 billion		
				2015	£2.8 billion		Butcher (2017)
				2014	£736 million	Installation of electrification equipment	Comptroller and Auditor General (2016)
				2016	£1.165 billion		
		Maidenhead and Cardiff	170 (approx.)	2013	£1.1 billion	-	Butcher (2017)
				2014	£1.6 billion		
				2015	£2.8 billion		
		Cardiff and Swansea	56 (approx.)	2014	£295 million	-	Comptroller and Auditor General (2016)
				2015	£381 million		
				2016	£433 million		

		South Wales Metro	-	2014	£295 million	-	Barry (2014)
				2016	£738 million		
		Manchester and Leeds	-	2014	£290 million	-	Butcher (2017)
		Oxenholme Lake District station and Windermere station	16.1	2014	£16 million		
		Selby and Hull	-	2015	£97.3 million	-	
		Wigan and Bolton	-	2014	£37 million	-	
		Bedford and Corby	-	2014	£1.18 billion	-	
		Liverpool and Manchester	-	2009	£100 million	-	The Telegraph (2009)

While the above results present costs in aggregate terms, the electrification costs are also widely reported as a rate per single track kilometre (STK). Atkins (2007) developed an electrification cost model and produced estimates of the infrastructure costs of electrification, for both capital and maintenance costs.

Table 17 presents the outputs of the model when applied to specified routes. It is shown that the infrastructure costs of electrifying an existing route range from £550k to £650k (approx. €617k to €729k)[7] per single track kilometre.

---

[7] In the last few years, the exchange rate between € and £ has fluctuated significantly. To calculate this approximation, the current (March, 2018) exchange rate of 1€=0.89£ has been used. Since the vast majority of the data from this literature review has been reported originally in £, we believe it is more informative to stick to the original sources due to the uncertainty and volatility that surrounds the exchange rate.

Table 17. Electrification Costs for Exemplar Routes (quoting Table 4.2 in Atkins, 2007)

Route	Sub-route	Capital Cost	Cost/STK	Total Route Cost/STK	Operational Cost/annum	Total Route Operational Cost/annum
MML	MML	£252,140,000	£649,845	£649,845	£983,000	£983,000
Chiltern	Marylebone - Snow Hill	£192,390,000	£531,464	£529,499	£917,000	£1,237,000
	Neasdon - Aylesbury	£53,911,000	£518,375		£264,000	
	Princes Risborough - Aylesbury	£6,270,000	£570,000		£56,000	
	Marylebone-Aylesbury	£66,697,000	£537,879		£314,000	
Cross Country	York - Leeds	£42,967,000	£565,355	£600,266	£193,000	£1,495,000
	Leeds/Doncaster - Sheffield	£47,483,000	£608,756		£198,000	
	Sheffield - Birmingham	£155,116,000	£625,468		£628,000	
	Birmingham - Bristol	£108,591,000	£577,612		£476,000	
	Derby - Birmingham	£75,562,000	£572,439		£334,000	
	Newcastle - Drem re-wire	£121,977,000	£356,658		£867,000	£867,000
	Newcastle - Edinburgh	£142,638,000	£356,595		£1,014,000	£1,014,000
GWML	Maidenhead - Didcot	£113,304,000	£590,125		£243,000	
	Heathrow - Didcot	£155,562,000	£580,455	£635,316	£340,000	£2,129,000
	Didcot - Bristol TM	£116,039,000	£557,880		£527,000	

	Severn Tunnel Jn - Cardiff	£86,483,000	£568,967		£193,000	
	Cardiff - Swansea	£73,355,000	£516,585		£360,000	
	Wootton Bassett - Severn Tunnel Jn	£74,199,000	£515,271		£365,000	
	Didcot - Oxford	£19,914,000	£524,053		£96,000	
	Reading - Bedwyn	£51,315,000	£523,622		£248,000	
	Reading - Newbury	£28,288,000	£523,852		£137,000	

Maintenance costs

Failures of OLE components often result in system failure and delays of the timetabled train service. Therefore, the OLE equipment is inspected and maintained to support the delivery of the specified route reliability and availability targets and to preserve system safety. Quoting Network Rail (2009):

"Maintenance costs for all OLE components are driven by degradation rates. Other than the long term wearing out of the contact wire, degradation rate is complex and not easily predictable, so inspection-based maintenance regimes are widely utilized. The understanding of the cause and impact of this degradation enables optimization of inspection regimes and allows the most effective remedial action to be carried out to prevent premature failure of the asset. For contact wire and catenary wire, repair and maintenance, other than small scale localised replacement, is not usually effective, hence renewal by wire run / tension length is the preferred and most cost effective option."

Atkins (2007) suggests that in general the infrastructure maintenance costs incurred are expected to amount annually to 0.4%-0.5% of the capital costs. Specific maintenance/operational costs estimated for individual routes are presented in

Table 17.

5.1.2 Trolley wire model

The trolley wire model (shown in Figure 2) is a simplified design of the overhead line system. It is widely utilised in tram/light rail systems which are operated at lower speeds (maximum speed: 60 km/h). Keen and Phillpott (2010) commented that the trolley wire model is favoured for both aesthetic (reduced visual impact) and cost reasons. Elimination of the catenary wire and droppers reduces the component count and installation complexity. Mast height could be reduced as there is no need to support a catenary wire, therefore enabling a degree of reduction in mast/foundation dimensions and costs.

Quoting Keen and Phillpott (2010):

"Elimination of the catenary wire may however require augmentation of OLE conductivity by introducing a second contact wire. Twin contact trolley wire arrangements are commonly utilised in UK tram schemes. However, the maximum support spacing for a trolley wire system is limited to 50m due to contact wire sag. For catenary systems on tangent track, the maximum support spacing is in the region of 60-70m. The requirement for additional trolley wire masts (and structure foundations) might therefore offset the cost savings of a trolley wire installation compared to catenary."

Capital costs

There has been much less cost data available for the trolley wire model. Keen and Phillpott (2010) summarised the major costs associated with simplified electrification on branch lines where the largest contributor was the installation of masts and overhead line equipment which costs £100k/single track km (STK). An overall capital cost of £276k/STK was provided from a case study on a less used branch line linking Liskeard and Looe in Cornwall with a length of 9 miles. The line speed is limited to 30 miles/hour with an operating a capacity of one train per hour. Quoting Keen and Phillpott (2010):

"*Assumptions are given below:*

1. *The trolley wire configuration is applied.*
2. *Vehicle costs, servicing facility costs are not considered.*
3. *45m average mast spacing (trolley wire system) = 22 masts/km. Conventional installation methods comprising metal support poles mounted to a concrete or piled (screw or vibration) base. Assumed to cost £3k per installation (£500 mast plus £2500 foundation cost), £66k per track km, £594k route total.*
4. *Overhead lines support components and wiring cost (single wire trolley system) £35k per single track km. Installation costs £10k per single track km. Cost Installed: £45k per track km, £405k route total.*
5. *Power supply costs £1-1.5 million. The low speed, low power requirement enables operation of a 750V DC OLE electrification scheme from two low power (300-400 kW) DC substations with one located at each end of the line.*
6. *Installation of track joint jumpers and rail cross bonding, £5k per single track km, £45k route total.*
7. *Signalling costs £400k.*

8. *Project delivery fees: £1 million*."

The installation cost of a similar case study of Keen and Phillpott (2010) (a 25-mile branch line between Par and Newquay) was £244k/STK. These indicate a notional cost of £250-300k/STK for the trolley wire model.

Maintenance costs

The maintenance cost data is largely lacking for the trolley wire model. It is driven by degradation rates of different OLE components which are designed for different technical life expectancies (Kirkwood et al., 2016). Duque et al. (2009) uses records of system failures from the previous 17 years and finds that annual failure rates for different components are of very low orders of magnitude. Researchers have calculated the average life span of contact wires as 15 years, while the remaining components maintain their operations for 40 years or more (Ho et al., 2006; Shing and Wong, 2008; Network Rail, 2009; Atkins, 2011).

The trolley wire model without the catenary wire may require augmentation of OLE conductivity by introducing a second contact wire. Such twin contact trolley wire arrangements are common in UK trams and European main lines without apparent problem since the catenary arrangement enables more consistent levelling of the two contact wires. However, a drawback of the twin contact wire arrangement is the relative difficulty of setting up and maintaining perfectly level contact wires, particularly on curved sections of track. This can cause rapid wear of the higher wire due to electrical erosion thus necessitating premature replacement of that contact wire. This can also intensify premature wear of the other wire and increases the possibility of wire alternation in the same tension length. This form of contact wire erosion would however develop at a comparatively slow rate in branch lines because of the relatively few pantograph passes (Keen and Phillpott, 2010). Therefore, specific maintenance strategies and the associated maintenance costs need to be considered from a long-term approach. Andrade (2008) outlined specific challenges for the application of a long-term approach to the rail industry: "*lack of data on maintenance costs; lack of data on degradation of different components of the infrastructure; the acquisition of data is not always timely for swift decision-making processes; asset degradation rates are slower, therefore needing more time for data collection; in case of asset breakdown, consequential costs can be difficult to assess*".

5.2 CBA of Trolley Wire model

The above results are used as a starting point for measuring the life cycle cost of the overhead line systems. In this section, we present the cost-benefit analysis (CBA) for the implementation of the simplified design of OLE model. The analysis has been made as general as possible to be adopted by any railway IM, even though some of the details are specific to the case study: the secondary railway line Bartolomeu-Zarnesti (Romania). The cost information comes from British studies (and these could be considered high in an international context). It is a non-electrified secondary line with a maximum speed of 80 km/h which allows consideration of both the catenary wire model and trolley wire model.

The aim of the CBA is to quantify and compare the cost and benefit profiles with the alternative configurations of OLE models. Given that the case study line is currently non-electrified and is powered by diesel, we will focus on the impact of electrification and compare the impacts of different configurations. We thus define the Do-Minimum scenario and Do-Something scenario as follows:

i) Do-Minimum scenario (DM): characterised by the traditional catenary wire model
ii) Do-Something Scenario (DS): characterised by the introduction of trolley wire model

The costs associated with the scenarios are approximated using average costs from the literature review. Specifically, we make the following assumptions for the CBA.

1. The overhead line configuration is the only difference between DM and DS scenarios. All other external factors remain the same. Vehicle costs, servicing facility costs are not considered. Revenue is irrelevant to the configuration.
2. The installation cost of the typical catenary system is £600k/STK out of the suggested range £550-650k by Atkins (2007).
3. The maintenance cost of the catenary system per annum is amount to 0.45% of the capital costs out of the typical range 0.4%-0.5% suggested Atkins (2007).
4. The installation cost of the trolley wire system is £280k/STK (ranges between £250-300k/STK according to Keen and Phillpott's estimation in 2010).
5. It is expected that the contact wire in trolley wire system will wear rapidly due to electrical erosion thus necessitating premature replacement of that contact wire which may lead to relatively higher maintenance cost on unit length of the wire. However, the overall maintenance cost of the trolley wire system is unclear.
6. Power supply is assumed to be 750V DC. Given the same power supply voltage, the actual energy consumption depends on the traffic level and thus assumed equal for the two scenarios. However, we note that in reality the voltage may be different on the trolley wire system, and it does not need to be restricted to the level assumed here.

Table 18. Installation and maintenance costs used in the CBA (2010 UK prices)

	Catenary Wire model	Trolley Wire model
Installation cost/STK	£600k	£280k
Maintenance cost/annum	£2.7k	?

For both scenarios, the following parameters are selected to underpin the analysis:

1. Track length: 23.9 km.
2. Time horizon: 40 years. This choice is driven by that the infrastructure which powers electric traction has an operational life of approximately 40 years (Network Rail, 2009), although the average life span of contact wires is around 15 years. The wire renewal cost in the meantime is included in the annual maintenance cost.
3. Discount rate: the analysis is built assuming a 3% discount rate.
4. Inflation adjustment: 1.18 (using ratio of RPI index from years 2010 and 2016, to convert data provided from 2010 into 2016 prices). All final values are provided in 2016 market prices.
5. Exchange rate: the above costs are converted to Euros using the average exchange rate in the base year 2016 (£1=€1.3).

For each scenario, we build a cost profile which includes the initial investment costs and the annual maintenance expenses over the lifetime of the OLE systems. Comparing the scenarios, capital cost is lower in DS scenario but the maintenance cost of the trolley wire model is unknown (although it is expected to be higher). Thus, it is not possible to provide a realistic full Life Cycle Cost (LCC) for the DS scenario.

In this context, one solution is to use the ‘switching values’ approach used by the Department for Transport (DfT, 2017) when information about the key impacts of a project is missing to calculate the NPV. The ‘switching values’ approach evaluates what change in the Present Value of Benefits (or Present Value of Cost savings) is necessary to achieve a predetermined level of NPV (for example, a NPV equal to zero). The analysis will be complemented with a judgement of how likely this change in PVB (or PVC) is to be realised.

In this particular case, we resort to answering this question: what is the critical maintenance cost of the trolley wire model to make the IM indifferent to the alternative models? In other words, we estimate the level of maintenance cost in the DS scenario that yields a Net Present Value equal to zero (NPV=0).

The following table presents the CBA outputs for the two scenarios. The total net present costs are the sum of all costs incurred over the period of time chosen.

Table 19. CBA outputs of the trolley wire model (impact on IM)

Infrastructure Manager (IM) Impacts			
			Time horizon=40 years; @3% discount
		Unit cost in 2016 Euro	**Present Value**
Do Minimum	Capital investment cost	€ 26,102,885	€ 26,102,885
	Maintenance Cost	€ 117,463/annum	€ 2,796,584
	Impact in Do Minimum		**€ 28,899,469**
Do Something	Capital investment cost	€ 12,181,346	€ 12,181,346
	Maintenance Cost	**€ 702,200/annum**	€ 16,718,123
	Impact in Do Something		**€ 28,899,469**
Net impact on IM	Capital investment cost		-€ 13,921,539
	Maintenance Cost		€ 13,921,539
	Present Value of Costs		**€ 0**

Table 19 shows that in this case study, the critical maintenance cost of the trolley wire model is €702,200/annum (shown in red) which leads to a NPV of zero. This means that if the maintenance cost is greater than this critical value, the trolley wire model leads to a greater LCC and that the traditional catenary wire model is cheaper. However, as long as the maintenance cost of the new model is not too large, it is an economically viable option. The critical value is almost six times higher than the comparable maintenance cost of the catenary wire model, or 5.76% of the capital cost of trolley wire model.

Our result shows that reduction in electrification cost could be realised by adopting simplified overhead lines model on less used lines. However, there is evidently a trade-off between the one-off capital cost and maintenance cost of the OLE system whole life cost and will need to be considered in conjunction with the IM capital/maintenance cost trade-off philosophy and any changes anticipated in connection therewith during the lifetime of the asset.

Additionally, the trolley wire model can only reach lower speeds than the catenary wire model, hence potentially leading to longer travel times in the route. On the other hand, compared to non-electrified lines (e.g. diesel locomotives), electrified vehicle has better acceleration characteristics, so they are much better suited to lines where trains stop and start regularly. So even if the trolley wire leads to lower maximum speed limits, compared to no electrification it might lead to faster journey times for some lines, due to the better acceleration. Altogether, the total impact on travel time is unknown and would depend on the number of stops and other features of the line. In the worst scenario, the initial lower investment costs would need to be traded off against slower journey times as well as potential increases in maintenance costs as suggested above. But it is also possible that travel time remains unaffected overall or, even better, is improved for lines with many frequent stops.

The development of battery technology and bimodal trains may alter the economics around choice of overhead line solution and could possibly make the trolley wire model un-economic. The cutting-edge technology of this area is advancing fast and we have not considered it as part of the NeTIRail-INFRA project.

It should be noted that in the NeTIRail-INFRA project, the technical work with respect to the Trolley Wire model has not enabled a full monetary estimate of the investment costs of the proposed system. Thus, the above information simply offers some observations based on data from GB rail.

5.3 Optimised wire tension

This innovation is related to optimization of existing equipment by way of considering the appropriate tension of the overhead wire. Wire tension is one of the controllable factors for overhead lines which influence the life cycle costs and maintaining the overhead line performance. The larger the forces between cables and pantographs, the quicker the contact wire wears (Kirkwood et al., 2016).

The proposed innovation is concerned with establishing the wire tension that optimises asset life and life cycle costs to be applied on the traditional overhead line system. It is expected that increased wire tension will result in smaller defects of the contact wire, reduced fatigue of the overhead line system and more rapid crack propagation, whereas less tension means less risk of tensile failure. However, quantifying the impact of this innovation on the life cycle cost requires the following data which is infeasible to obtain within the timescales of this project.

- the change in the cost of equipment/components that will be affected
- what will be the change in the asset life (uncertain at this stage)
- the change in maintenance/renewal plans
- unit cost of maintenance/renewal, and changes associated with varying tension

5.4 CBA of on-board overhead lines monitoring

Failures of individual OLE components often result in system failure which can lead to delays of the timetabled train service. Therefore, it is important that inspection and maintenance of the OLE is carried out to uphold system reliability and to schedule maintenance for individual components based on the condition that they were found to be in during routine inspections.

Task 3.4 is titled "Controllable factors for existing overhead lines: maintaining performance at lowest life cycle cost". Within this task, several technologies are explored which aim at improving the monitoring of existing overhead lines and to gather information that helps to reduce life cycle costs.

In this section, we develop a CBA model for one of these monitoring technologies. The proposed framework can be easily applied to any of the other overhead line monitoring technologies, since the list of main costs and benefits is very similar across technologies. Only the amount of investment costs and the type of information produced will vary.

The technology evaluated in this section is an on-board monitoring system of voltage, power spikes and other electrical properties that inform about the state of substations and overhead line.

5.4.1 Detailed description

System for on-board monitoring of voltage and current consuming.

Quoting NeTIRail-INFRA Deliverable D3.5 (p.9):

"The system developed under this sub task is represented by the ECVM - Equipment for Current & Voltage Monitoring - and also the Software Application related to it, for collecting and saving data.

This equipment is designed for monitoring the electricity supply of the locomotive, using two parameters. First parameter measured is the voltage at the entrance to the train, from the pantograph; the second value measured is the current absorbed through the main transformer. High frequency sampling of the acquisitioning values will allow the system to register voltage "spikes" and fast variations of the current absorbed from the railway power supply system, through pantograph.

Knowing a complete image of the electrical parameters and the quality of the electric contact between pantograph and contact line, optimisations could be made. Also, could be earlier identified the structure defects on the contact wire but also on the carbon stripe of the pantograph.

For system protection, the inputs and outputs are galvanic isolated; also the connections of power supply and data communication with the Laptop are galvanic isolated".

5.4.2 Investment costs

€500 per ECVM (Equipment for Current & Voltage Monitoring) device (located on-board): 1 device needed to cover one route.

€1,000 for a computer (on-board) that collects and stores the data (i.e. the Software Application). This can be classed as 'data server/communication' costs. The total estimate of €1,500 investment cost has been provided by ADS Electronics, partners of the project who developed the innovation as part of WP3. The life of these two assets is approximately 5 years.

The following graph shows the cost profile for this innovation for a time horizon of 10 years (i.e. two full life cycles). 10 years is chosen for simplicity (there are no complexities so the results can easily be extended for longer periods) and to allow comparability with other monitoring technologies from WP4 evaluated in section 6.

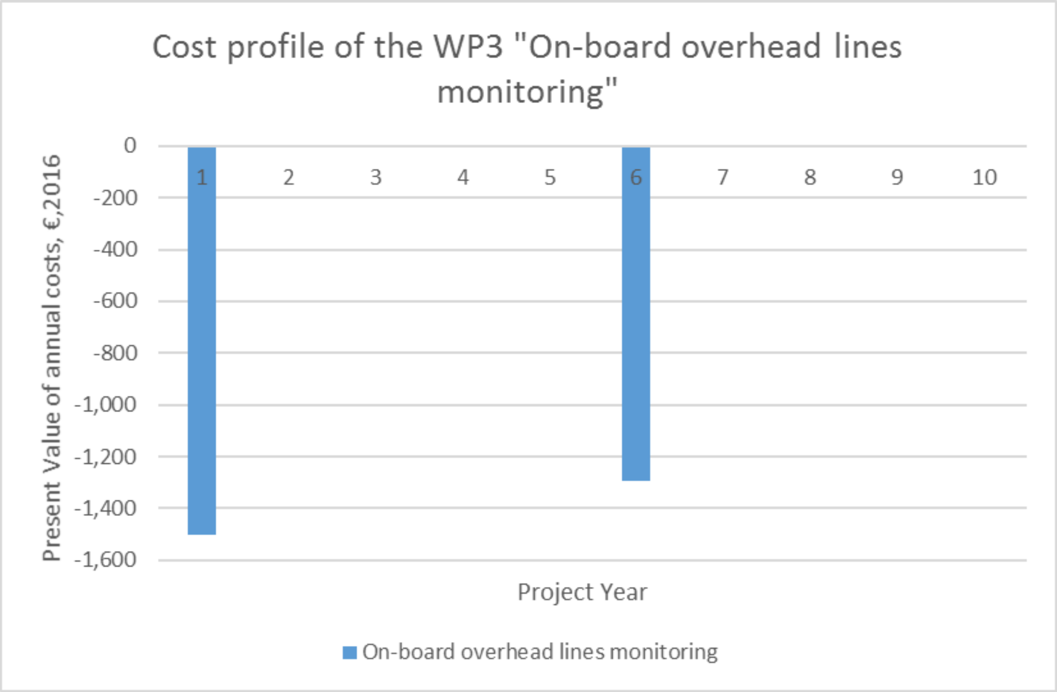


Figure 8. Costs of on-board overhead line monitoring

This innovation only requires a one-off investment of €1,500 every 5 years. Of course, there are also additional labour costs of monitoring, such as understanding and making use of the data. However, we assume that monitoring labour costs will be incurred anyway by the IM, regardless of what technologies are used to assist the process. In other words, this monitoring innovation simply aids the current inspection regime, rather than replacing any labour costs.

5.4.3 CBA output

The CBA of this innovation is conducted at a generic level, without assuming any particular case study of application. This is so because: i) we only observe the costs of investment, which do not vary by route, and ii) the benefits, which will be specific by route, cannot be observed.

Before explaining the approach taken, we shall expand upon this limitation. The main benefit of this monitoring technology is the generation of information, to be used by the IM for a better understanding of the conditions of the line and hence improved decision-making. Since it is not known how the IM will use the information to change their maintenance strategy (e.g. more preventive and less corrective) to reduce costs, the precise benefits of the innovation cannot be calculated.

In this context, we resort to the 'switching values' approach used by the Department for Transport (DfT, 2017) given that some key information is missing.

The following table provides the summary of the CBA outputs for this monitoring innovation. For ease of use of the information, we divide the total net present costs by the time horizon considered (10 years) to calculate the amount of average annual savings needed to achieve a NPV=0.

Table 20. CBA outputs of the on-board overhead lines monitoring

		Overhead line monitoring	
		Time horizon=10 years; @3% discount	
		Type of analysis: generic, for any line	
		Details: on-board monitoring of voltage and current consuming (one device per route)	
Costs (by stakeholder)			
Infrastructure Manager			
Capital investment costs		-€ 931.30	
Maintenance costs			
Data server/communication costs		-€ 1,862.61	
Total Costs over time horizon		-€ 2,793.91	
Average annual cost		-€ 279.39	
Benefits needed (by stakeholder) for NPV=0			
Infrastructure Manager			
Life cycle cost (LCC) savings (M&R)		€ 279.39	
Increased track availability		(+)	
Rail users			
Delay reductions		(++)	
Safety risk reductions		(+)	

The table shows how much is the average annual cost saving (in net present value) that would recover the investment at the end of the period. For this innovation, this is equal to €279 per year. If the IM is able to save at least this amount per year thanks to the technology, then it is worth the investment from the perspective of IM savings only.

However, this is only a ‘worst-case’ scenario where no other benefits occur. In reality, we expect the information from the device to be used to prevent failures in the system. If that is the case, delays will be avoided, safety risks reduced, and the line will be available longer (i.e. not closed due to failures or speed restrictions). These additional benefits have been represented with a (+) sign, or (++) if the effect is expected to be larger. If those added benefits occur, then the benefits associated with their prevention can easily be larger than the €279 figure, making the investment worth it even if no costs were saved from the maintenance side.

In summary, this is a very low-cost technology that produces information with the potential to prevent failures and improve the maintenance/renewal strategy of a rail electrified line.

6. Cost-Benefit Analysis of WP4 innovations

In this section, we present the cost-benefit analysis (CBA) for the implementation of the innovations from WP4. The analysis has been made as general as possible to be adopted by any railway IM, even though some of the details are specific to the case study: the secondary railway line Bartolomeu-Zarnesti (Romania).

The innovations of WP4 aim at enhancing the possibility to monitor the quality of the railway network. With access to better information it is feasible to adjust the pattern of maintenance activities and ultimately to save on tracks' life cycle costs and also to reduce the risk for train disturbances. WP4 addresses the pros and cons of the following innovations:

- Task 4.1 On-track monitoring for S&C and turnouts
- Task 4.2 ABA, on-train monitoring
- Task 4.3 Smartphones, on-train monitoring

6.1 CBA Scenarios

The aim of the CBA is to quantify and compare the cost and benefit profiles with and without the innovation, over a given time period of the case study. Since the same case study line is used for the three innovations, the analysis can be simplified by establishing a common Do-Minimum scenario and defining a specific Do-Something scenario for each innovation. We define these scenarios as follows:

i) Baseline scenario (Do-Minimum): characterised by the current strategy and implementation of maintenance activities.
ii) Do-Something Scenario (DS): characterised by the **introduction of new monitoring devices** to obtain more regular and detailed information about the condition of the rail. One Do-Something scenario per innovation (i.e. monitoring device) is defined, namely:
    - DS1: ABA system (task 4.2)
    - DS2: On-train monitoring smartphones (task 4.3)
    - DS3: On-track monitoring for turnouts and S&C (task 4.1)

The time horizon used is 10 years for DS1 and DS2 and 9 years for DS3. This choice is driven by the asset with longest life, namely the ABA system with an expected life of 10 years. However, there is uncertainty around the actual life of this new technology, and the engineers who developed the system believe that it might even be longer. We choose to stick to the 10-year life to be conservative. For DS3, 9 years instead of 10 is used to simplify the analysis, given that the life of the devices developed in Task 4.1 have an expected life of 3 years and we would simply deal with 3 full cycles of replacement.

It may be worth repeating that the use of different time horizons for the respective innovations is methodologically consistent. Each new technology is considered in isolation from the others, and the result indicates if that intervention is motivated. Two or more innovations may be warranted, or indeed no-one of the options considered. What is of importance for the analysis is for the life of all technical components to be consistent *within* each innovation, while different innovations can have different time horizons.

6.2 Do-Minimum scenario: a continuation of current technologies and practice

This scenario assumes that the railway will continue operating as usual, i.e. adopting the same maintenance strategies and therefore observing similar costs as now.

The table below summarises the annual total maintenance and renewals costs for the line Bartolomeu-Zarnesti using data from 2014 and 2016. The costs have been provided by the Romanian railway RCCF. While this information is not necessarily representative of an average year, it is the only data available. All available details on the cost categories are shown in the appendix.

Table 21.All yearly costs, maintenance and renewals (2014 and 2016 data), for the Bartolomeu-Zarnesti corridor.

Cost category	2014 costs (€)	2016 costs (€)
Inspection	14,000	14,000
Preventative	11,000	3,000
Corrective	137,000	45,000
Personnel and Training	56,000	58,000
Other	12,000	12,000
Total I,M&R	**230,000**	**132,000**
Operation	**269,000**	**365,000**
TOTAL	**499,000**	**497,000**

There are significant differences between the two years of data, and the reasons for these have been explained by the IM and are provided in the appendix in full detail. The two main differences are the following:

- Lower corrective maintenance costs in 2016, due to a lower need thanks to work conducted in the past.
- Higher operation costs in 2016, due to significant increases in salaries for the operation personnel.

This secondary line incurred a total cost of €230,000 for maintenance and renewal activities in 2014, and only a total of €132,000 in 2016. Of those activities, we are particularly interested in the split between preventive and corrective activities. This may indeed be the same activity such as tamping or grinding tracks at spots where quality is inferior. The distinction is rather in what triggers the intervention; when it is corrective the trigger is that there is an imminent risk of train disturbance or the disturbance has already occurred, while a preventive intervention is done at an earlier point of time and it can be planned well in beforehand (and therefore less costly). To assess the value of a new monitoring technology, it is therefore crucial to observe the current strategy in terms of how much is spent on preventive and corrective actions, respectively.

Since the corrective maintenance varies significantly between the two years, it was agreed that the best solution is to work with a simple average as a proxy for the costs of a representative year. The same averaging solution is applied to all other cost categories, except for operation, since that difference is driven by salaries increase and hence the latest figure for 2016 is likely to be representative of future costs. The following table presents the average of both years and converts these into market prices for CBA purposes, as outlined in the Methodology section. Operation costs are excluded from the table as these will not be affected by the WP4 innovations.

Table 22. Representative yearly costs: 2016 factor and market prices (Bartolomeu-Zarnesti)

Cost category	Base year (2016) factor prices	Base year (2016) market prices
Inspection	14,000	16,660
Preventative	7,000	8,330
Corrective	91,000	108,290
Personnel+Training	57,000	67,830
Other	12,000	14,280
TOTAL	**181,000**	**215,390**

The annual costs for the line amount to a total of €181,000 for inspection, maintenance and renewal activities, which converted to market prices equal to €215,390.

In general, we can define preventive maintenance (PM) and corrective maintenance (CM)[8] as follows:

PM = Inspection + Preventive tasks

CM = Corrective tasks

Other costs (personnel, training and other) incurred cannot be easily attributed to preventative or corrective maintenance. For instance, we could assume that staffing costs are incurred regardless of the strategy, or that they are proportional to the other spending on PM and CM. If we ignore “other costs”, the annual total cost of PM is equal to €21,000 and the total cost of CM is equal to €91,000. If we attribute “other costs” proportionally to PM and CM, the total PM and CM costs would be €33,900 and €147,100 respectively. Either way, this implies a split of 19%-81% between PM and CM for the Romanian railway IM in the recent years.

There are few studies providing clear empirical evidence on the PM-CM split for railway infrastructure maintenance. A recent study investigating the PM-CM relationship in the Swedish railway (Stenstrom et al., 2016), reveals significant difficulties in attributing costs to preventive and corrective categories.

---

[8] For simplicity, we use the terms PM and CM, but it must be noted that these include both Maintenance (M) and Renewals (R), as shown in the table 21 above.

Consequently, their results must be interpreted carefully. Stenstrom et al. (2016) found that PM is typically between 10% and 30% of the total maintenance costs (however, these figures correspond to a more holistic measurement of total costs that include associated user delay costs as well, which are accounted as CM). If user delay costs were excluded (part of the CM), and assuming PM stayed the same, then the PM share would be higher than the 10-30% range reported in their study. Perhaps more importantly, Stenstrom et al (2016) also shows that railway sections with the lowest total maintenance cost are associated with having the highest share of PM. In other words, being able to undertake preventive maintenance tends to make the overall maintenance cheaper, as it is expected.

For the construction of the cost profile of the Do-Minimum scenario, we shall assume that costs from 2014 and 2016 are observed every year in an identical fashion, with no changes.

6.3 Do-Something scenarios: evaluating the implementation of new monitoring technologies

To evaluate the new monitoring technologies, information about their capital and implementation costs is needed as well as how large cost savings and additional benefits may be. To estimate the cost savings arising from new monitoring technologies we would however need to understand their impact on the Infrastructure Manager strategy in terms of PM and CM. Since this information is not available, it is necessary to make assumptions on how the PM-CM balance will shift because of the new equipment. This is because the technology provides information that would be worthless if the IM decides to ignore it and continue doing business as usual (e.g. keeping the current PM-CM split).

Unfortunately, it is not possible to make precise realistic assumptions about the change in the IM strategy. In general, it is only reasonable to assume that the IM will increase the amount of Preventive Maintenance (PM), consequently reducing failures/disturbances and hence Corrective Maintenance (CM). The extent of change will depend on the accuracy of the new monitoring devices (rate of detection success), the probability of failures and ultimately, the IM decision-making.

In practical terms, this means that it is difficult to provide realistic cost profiles for the Do-Something scenarios. Arguably, it would also be of little help to IM decision-makers who also might not know what PM-CM changes are realistic or not. To avoid making strong assumptions and with the goal of facilitating decision-making, the subsequent evaluation will instead attempt to answer the following question: what level of cost savings is necessary to make the investment worthwhile? This question is addressed for different DS scenarios as described earlier, one for each of the monitoring devices developed.

The possibility of additional benefits from delay reductions is also discussed, but inclusion in the DS cost profile is not possible to due to lack of information about the current delays. Similarly, there may be fewer speed restrictions thanks to better knowledge about the track condition. An example is, however, provided to show how large these benefits may be for a range of delay reductions scenarios.

6.3.1 Investment costs for each innovation

The following information is available for each of the three monitoring technologies, with respect to their associated investment and running costs and their asset life:

- **DS1: ABA system (task 4.2)**
  - **Price**. Full ABA package price will approximately be €100,000.
  - **Quantity**: One ABA package is installed in a train operating on the Bartolomeu–Zarnesti route.
  - **Running costs**: Costs associated with data communication and storage are assumed to be part of the full ABA package price. Any relevant costs are included in the ABA package price.
  - **Asset life and maintenance costs**: the core of the ABA system has an expected life of approximately 10 years (however, there is significant uncertainty at this end and experts consider the possibility that the device can last even longer). Small sensors need replacing when not working, and this is estimated to cost around 5,000€ per year. Cables need replacing after 5 years and would cost around 2,000€.
  - **Other**: Patent costs, intellectual property, know-how and similar costs are not known and are excluded from the analysis. It is also not clear whether an IM would have to incur these costs.

- **DS2: On-train monitoring smartphones (task 4.3)**
  - **Price**: for one smartphone, 150€-200€. Plus, data communication costs of 20€ per month per smartphone.
  - **Quantity**: 1 smartphone per route, i.e. 1 smartphone to be installed in one train covering the route Bartolomeu–Zarnesti.
  - **Running costs**: central data servers and networking cost 3,000€ per year. How many of these servers are installed depends on the strategy for implementation, e.g. 1 server per Infrastructure Manager or one shared over multiple IM, as they could be share across routes. For the analysis we assume one server exclusive for the Bartolomeu-Zarnesti route.
  - **Asset life**: the expected asset life per smartphone is 2 years. This has been estimated by the developers of the innovation based on the battery life, as it is standard procedure in the industry. No other maintenance costs are needed on top of the cost of replacing the smartphone every 2 years.
  - **Other**: Patent costs, intellectual property, know-how and similar costs are not known and are excluded from the analysis. It is also not clear whether an IM would have to incur these costs.

- **DS3: Turnouts and S&C monitoring devices, plain-line accelerometers (task 4.1)**
  - **Quantity.** This monitoring technology is made up of various devices, namely sensors (WSDR type) and supplementary concentrators (WCDR) and long-range communication devices (WLRCD). The number of devices needed to cover one route depends on the characteristic of the route. For the case study line, the following devices are needed:
    - For the 10 railway switches in the line:
      - 4 sensors (WSDR) for every switch;

    - 1 concentrator (WCDR) and 1 long range communication device (WLRCD) for every group of 4 WSDR (every switch);
    - Total: 40 WSDR; 10 WCDR; 10 WLRCD
  - For the 11 bridges:
    - 4 sensors (WSDR) for every bridge, i.e. 2 sensors for every end of bridge;
    - 1 WCDR and 1 WLRCD for every end of bridge, means 2 WCDR and 2 WLRCD for every bridge;
    - Total: 44 WSDR; 22 WCDR; 22 WLRCD
  - For the 3 curves with small radius:
    - 4 sensors (WSDR) for every radius;
    - 1 WCDR and 1 WLRCD for every group of 4 WSDR (every radius);
    - Total: 12 WSDR; 3 WCDR; 3 WLRCD;

In total, 96 WSDR; 35 WCDR; 35 WLRCD devices are needed to cover the line:

- **Price**: each sensor can cost between 50€ and 75€ if a package of at least 100 devices is bought. The price is evaluated as being the same regardless of the device type because they compensate the expense of the photovoltaic cells resin with the expense of the microcontroller (Wi-Fi microcontroller for WLRCD). Evaluation is for at least 100 pcs, because this is a general price for such electronic components. Since WSDR and WCDR use the same microcontroller, and they are more than 100, a price in the range of €50-€75 can be considered. The WLRCD are less than 100 pcs. and use another microcontroller; a realistic price range should be 20% higher. Additionally, data communication costs must be included. The WSDR and WCDR devices are free in terms of communication costs; only WLRCDs need a contract for Internet service provider; and this is the maximum number, because some locations are not in coverage area for the Internet. When no Internet communication is possible, the WLRCD will work as a Data Logger, saving internally information for weeks, and will be downloaded by the operator through Wi-Fi directly. To be on the safe side, we can assume a cost of 10€ per month per WLRCD (depending on the data provider), i.e. 120€/year per each of the 35 WLRCDs.
- **Running costs**: central data servers and networking can cost approximately 3,000€ per year. The price would depend on how many sensors are linked to the server, but 3,000 seems a fair proxy. At the network level, how many of these servers are installed depends on the strategy for implementation, since they could be shared across routes and regions (e.g. 1 server per Infrastructure Manager, one shared over multiple IM, or one per route). For the analysis we assume one server exclusive for the Bartolomeu-Zarnesti route, which is the most expensive scenario.
- **Asset life**: the expected life of the device is 3 years. This has been estimated by the developers of the innovation based on the battery life, as it is standard procedure in the industry. No other maintenance costs are needed on top of the cost of replacing the device every 3 years.
- **Other**: Patent costs, intellectual property, know-how and similar costs are not known and are excluded from the analysis. It is also not clear whether an IM would have to incur these costs.

There are other costs associated with the technology, such as the human labour needed to make use of it, e.g. processing the data. However, since the line already incurs labour costs for track inspection costs, we will assume that the existing time will be diverted to perform the same inspection tasks but now making use of the new technology. Therefore, we assume no additional costs – on top of those reported above - are incurred in comparison with the Do-Minimum scenario.

The following table summarises the investment and running costs of the new monitoring technologies.

Table 23. Capital and running costs of WP4 monitoring technologies

Technology	Capital	Data communication costs	Data servers	Sensors maintenance	Other maintenance
DS1: ABA system (4.2)	100,000€ (one-off payment). Asset life is 10 years			5,000€/year	2,000€ every 5 years (cables replacement)
DS2: On-train monitoring smartphones (4.3)	Between 150€ and 175€ every 2years	240€/year per smartphone	3,000€ per year		
DS3: Turnouts and S&C Monitoring (4.1)	WSDR = 50-75€; WCDR = 50-75€; WLRCD = 60-90€; Need a line-tailored combination of these; Asset life for each is 3 years	120€/year per WLRCD device			

6.4 CBA Outcomes for WP4 innovations

6.4.1 Costs

What level of cost savings is needed to make the investment worthwhile? In other words, we estimate the level of cost savings needed to obtain, at least, a Net Present Value equal to zero (NPV=0). In this section, this question is addressed for three different DS scenarios, each comprising one monitoring technology independently from the others. Complementarity among the three devices will be discussed at the end.

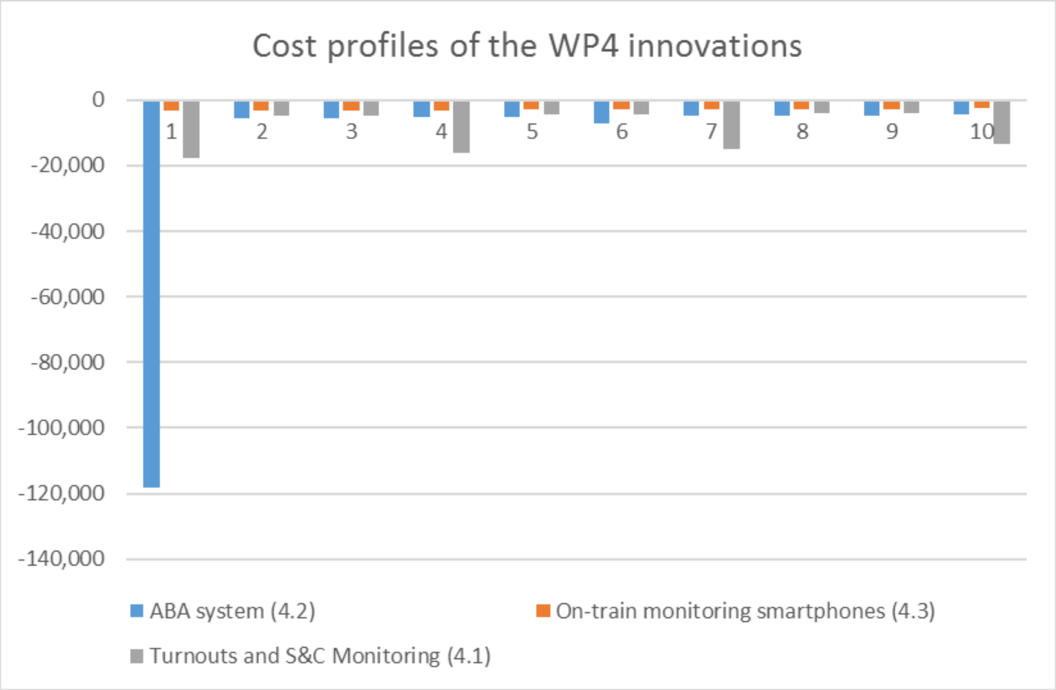
For each DS scenario, we build a cost profile which includes initial investment and several categories of running costs over the lifetime of the technology. These cost profiles are a changing component of the Life Cycle Costs (LCC) when comparing DS and DM. Critically, they are the only cost change that we do observe with certainty, since other cost savings are completely dependent on the IM strategy and are unknown to us. The table below shows a basic cost profile for all DS scenarios, for a 10-year period.

Table 24 Capital and running cost profiles over a 10-year period (2016 market prices, discount rate=3%)

Year	ABA system (4.2)	On-train monitoring smartphones (4.3)	Turnouts and S&C Monitoring (4.1)
2016	118,168	3,415	17,740
2017	5,736	3,316	4,819
2018	5,569	3,219	4,678
2019	5,407	3,125	16,235
2020	5,250	3,034	4,410
2021	7,135	2,946	4,281
2022	4,948	2,860	14,857
2023	4,804	2,777	4,035
2024	4,664	2,696	3,918
2025	4,528	2,617	13,596
Total Net Present Costs (€, 2016 prices)	**166,211**	**30,005**	**88,569**

The following figure shows the profiles graphically. These are the additional costs that the new technology would impose on the Infrastructure Manager with respect to the current situation.

Figure 9. Cost profiles of the WP4 innovations: investment and running costs



The costs included in the table and figure are expressed in 2016 euros, discounted at 3% and assume no changes in current capital and running cost estimations. The total net present costs are the sum of all costs incurred over the period of time chosen. An important distinction among the systems is the higher initial investment required for the ABA system compared to the other technologies. As it was discussed earlier, this extra cost can be linked to higher quality, since the ABA technology is likely to be more powerful in its analysis of the rail track health condition. Running costs of ABA are also higher (approximately 70%) than those of smartphones. In general, smartphone monitoring devices are the cheapest even though they need continuous replacement. With respect to the third technology (DS3), the costs are specific to the demands of the Bartolomeu-Zarnesti route, and hence it is more difficult to draw general conclusions. It seems, though, that its costs can be somewhat in the middle of the other two monitoring technologies.

6.4.2 Benefits

If additional benefits such as reduction of delays are realized, then the investment in monitoring would be worth it even if only a lower maintenance and renewal cost saving was achieved via a new PM-CM balance. In other words, we shall see in the final CBA (next section) that the initial figures of necessary cost savings assume that no other benefits arise.

If information on track failures and the consequent delay minutes was available, then it would be possible to approximate the additional benefits from reducing delays in the line. Information is available on failures, but unfortunately no information of delays. In this section we discuss, with the aid of an illustrative example, how large these delay reduction benefits might be.

The following table shows details on the failures that occurred on the line during 2014.

Table 25. Failures during 2014 (Bartolomeu-Zarnesti line)

Failure mode	component	number of failures
(Track) -> Rail defect identified - clamp and/or speed limits applied	Sleepers	16
(Track) -> Rail defect identified - clamp and/or speed limits applied	Fittings and Fastenings	27
(Track) -> Rail defect identified - clamp and/or speed limits applied	Rail	8
(S&C) -> Signalling/electrical failures		36
(S&C) -> Ice, ballast or other object between switch and stock rail preventing switch locking	Rail	8
(S&C) -> Crossing failure	Fittings and Fastenings	14
Total		109

Potentially, the new technology could have helped to prevent a maximum of 109 failures in 2014. Presumably, these failures have caused a serious amount of disruption in the line, and therefore we can argue that additional benefits in the form of delay reductions (or fewer speed restrictions) are likely to occur in this line if the monitoring technology is implemented. We are not aware of the safety implications of the recorded failures. Had these failures had safety risks associated with them, an additional benefit would also occur in the form of safety risk reduction.

The schedule for the Bartolomeu-Zarnesti line includes 18 trains, 9 in each direction. For a typical day, approximately 1,350 passengers use this line. This means that the approximate average load is 75 passengers/train.

If delays occur, each minute of delay bears a time-cost to the passengers, which can be approximated with information on the value of travel time savings for Romanian citizens. Limited evidence is available from a European meta-analysis of values of travel time (Wardman et al., 2012). The values are provided by distance and trip purpose. The length of the Bartolomeu-Zarnesti line is 23.9km. Based on the surveys conducted as part of the NeTIRail-INFRA project (reported in Deliverable D5.2), the purpose share is as follows: 76% commuters, 1% business travel and 23% other purposes (including leisure, trips to hospitals, etc).

For this type of line and rail travellers profile in Romania, Wardman et al. (2012) report values of time (VoT) of 1.98 €/hour for commuters, 6.68 €/h for business travellers and 1.71 €/h for other purposes. These values are in 2010 prices. We acknowledge that these values do not come directly from surveys in Romania, and hence their validity may be questionable. However, it is the only available estimate for the Romanian rail context that we are aware of and they are arguably of a modest magnitude. Thus, this should be seen only as an illustration of a conservative estimate of the delay reduction benefits.

At the same time, it is also well known that delay time is perceived to be costlier – to be more of a nuisance – than standard in-vehicle travel time. The study points towards a lateness multiplier of 3 for train travellers (Wardman et al., 2012), meaning that the value of one minute of delay is 3 times the value of one minute of in-vehicle time. Hence, the VoT reported above must be multiplied by 3 to obtain the value of 1 minute of delay.

The following table shows the original values and their conversion to be used for our analysis:

Table 26. Estimates of values of time (Romania)

	Values of time in Romania, by purpose, for rail travellers (line length=25km)		
	Commute	Other	Business
VoT, €2010 (per hour)	1.98	1.71	6.68
VoT, €2010 (per minute)	0.03	0.03	0.11
VoT, €2016 (per minute)	0.04	0.03	0.13
Value of late time, €2016 (per minute)	0.12	0.10	0.39

To build an illustrative example, assume that the monitoring devices will help to prevent 5 failures per year, each causing a 20-minute delay to only 1 train. No knock-on effects are assumed to exist, since there is only a maximum of 2 trains every hour in this secondary line. We also assume that the effect will not create new demand for the line, i.e. all benefits accrue to already existing passengers. In this case, the total benefit of avoiding these 100 minutes of delay to passengers can be calculated as:

$$Delay_{benefit} = \Delta Delay\_minutes * Value\ of\ late\ time$$

Where *ΔDelay_minutes* represent the change in delay minutes in the Do-Something scenario. Assuming *ΔDelay_minutes*=100, and taking into account the current trip purpose split, the average benefit for 100 minutes per passenger (weighting by purpose) is €11.56. Multiplying by the load factor of 75 passengers/train, saving 100 minutes of delay would generate a benefit of approximately €867.

To put this into context, these benefits represent approximately 30% of the yearly cost savings needed to make the smartphone devices worth the investment. Hence, they are of substantial magnitude relative to the size of the investment needed. Additionally, other benefits may accrue directly to the operator, such as increased demand in the long term if services are perceived as more reliable by the public.

Summing up, if a high amount of delay minutes was eliminated, the additional benefits derived from the monitoring technologies have the potential to be very significant.

6.4.3 Summary

The following table provides summarizes the results of the CBA for each innovation. For ease of use of the information, we divide the total net present costs by the time horizon considered (e.g. 10 years) to calculate the amount of average yearly savings needed to achieve a NPV=0. This tells us how much is the average cost saving (in net present value) that would recover the investment at the end of the period. Of course, if an asset (e.g. ABA system) had a longer life than the time period, it will have additional value beyond the time horizon considered.

Table 27. CBA of WP4 innovations summary

	Costs and Benefits					
	4.1 (S&C and turnouts monitoring)		4.2 (ABA)		4.3 (Smartphones)	
	Time horizon=9 years ; @3% discount		Time horizon=10 years ; @3% discount		Time horizon=10 years ; @3% discount	
	Type of analysis: line specific (Bartolomeu-Zarnesti, Romania)		Type of analysis: generic, for any line		Type of analysis: generic, for any line	
	Details: 96 WSDR; 35 WCDR; 35 WLRCD to cover 10 railway switches (40 WSDR), 11 bridges (44 WSDR) and 3 curves with small radius (12 WSDR)		Details: 1 ABA system per line		Details: 1 monitoring smartphone per line	
Costs (by stakeholder)						
Infrastructure Manager						
Capital investment costs	-€ 35,170.16		-€ 118,168.32		-€ 1,537.57	
Maintenance costs			-€ 48,042.23			
Data server/communication costs	-€ 39,802.29		*(included above)*		-€ 28,466.99	
Total Costs over time horizon	-€ 74,972.45		-€ 166,210.55		-€ 30,004.56	
Average annual cost	-€ 7,497.25		-€ 16,621.05		-€ 3,000.46	
Benefits needed (by stakeholder) for NPV=0	(1) If only LCC savings	(2) Moderate user benefits	(1) If only LCC savings	(2) Moderate user benefits	(1) If only LCC savings	(2) Moderate user benefits
Infrastructure Manager						
Life cycle cost (LCC) savings (M&R)	€ 7,497.25	€ 6,630.25	€ 16,621.05	€ 15,754.05	€ 3,000.46	€ 2,133.46
Increased track availability	N/A	N/A	N/A	N/A	N/A	N/A
Rail users						
Delay reductions (100 delay minutes/year)	(++)	€ 867.00	(++)	€ 867.00	(++)	€ 867.00
Safety risk reductions	(+)	(+)	(+)	(+)	(+)	(+)
Comfort improvement	N/A	N/A	N/A	N/A	(+)	N/A

The first column for each innovation shows the level of cost savings needed to recover the investment, if no other benefits arise. Therefore, this can be taken as an extreme case. The second column shows how much the required cost savings would be if a moderate delay reduction was achieved – in line with the illustrative calculation done above for a yearly 100-minutes delay reduction. Still, we regard this as a conservative scenario. Note also that other benefits (reflected with + sign in the table) might be realised, therefore increasing the value of the innovation and reducing the need for LCC savings that make the investment worth it.

For Smartphones to be worth the investment, an average annual cost saving of €3,000 will suffice; Based on the 2014-2016 data for the Romanian line Bartolomeu-Zarnesti, €3,000 represent only a 2% cost saving from the overall maintenance and renewal costs assumed for a representative year (€181,000). As it was noted earlier, the existing strategy of the Romanian IM (RCCF) around this line reveals a 19%-81% split between PM and CM. Therefore, it seems realistic to assume that there is scope for an increase in the PM share in a way that total costs can be reduced.

For turnouts and S&C devices, the necessary cost savings are slightly larger, just above €7,000 per year (note that we have used a 9-year horizon instead of 10, but this would barely impact on the annual cost savings figures). This cost saving would represent a 4.5% of the approximate total yearly maintenance and renewal costs for the Bartolomeu-Zarnesti line. For the ABA system, the savings needed are even larger (around €16,5k/year for a 10-year period; i.e. 10-11% of the line costs), but the system has a higher potential to unlock cost savings via higher information quality about the track health and condition, as revealed by the tests performed in Romania.

6.4.4 Complementarities across different monitoring devices

The three technologies analysed here may have some degree of complementarity. First, turnout and S&C devices deal with specific parts of the track, presumably with more precision than the other devices. Therefore, these devices can be regarded as complements to the other technologies.

Secondly, the ABA system and smartphones may be regarded as substitutes in the sense that they both deal with detecting track failures generally. However, smartphones are also designed to pick up train vibration information in a way that can be used to study and improve comfort in passengers' ride. Also, smartphones are reasonably cheap and do not require a high initial investment, which could lead IMs to opt for a combination of both technologies anyway. This would be especially the case if data server communication costs could be shared among devices. So far, we have assumed that every device will incur its own data server and communication costs independently of the rest in an attempt to provide independent evaluations. However, it is possible that these costs are shared, increasing the argument for complementarity.

6.5 WP4 CBA Conclusions

New monitoring technology can generate frequent – in principle real-time – information about the health of the rail tracks. This information can be valuable for the railway IM, as it can facilitate a better and cheaper track maintenance strategy. In this section we have assessed the implementation of three new monitoring devices developed as part of the NeTIRaiL-INFRA project. All systems have a clear potential to unlock cost savings via a higher proportion of preventative maintenance, but they differ in their cost and the quality and type of monitoring they provide.

The ABA system (task 4.2) is a relatively expensive one-off investment but with clear returns in the long term, by enabling the IM to reduce costs via a new PM-CM balance with a higher PM share. Additionally, by reducing failures (currently up to 109 yearly failures in this line might be prevented), it can also: i) reduce train delays and all associated costs to passengers and IM (e.g. extra hours and revenue loss from reduced demand in the long term), ii) increase safety.

The other two monitoring devices – namely, on-train monitoring smartphones (task 4.3) and the turnouts and S&C monitoring devices (task 4.1) – deal with more specific problems/parts of the track and therefore, relative to the ABA system, have a somewhat reduced scope for increasing preventative work. However, their much lower costs make them a relevant option for providing information that may save costs even in the short term without the need to commit to a high upfront financial investment. A combination of ABA plus the smartphone devices is barely more expensive than only ABA and is expected to provide higher amount of information and hence more chances of optimizing the maintenance strategy to save costs. The turnouts and S&C devices are more specific and their usefulness to the IM would likely depend on the amount of failures related to those specific parts of the track and the possibility to save expensive corrective work there.

7. Overall conclusions of the economic appraisal

In this section we provide the overall conclusions after having performed an economic appraisal for all the different technological innovations proposed by NeTIRail-INFRA.

In most (if not all) industries, technological innovations may improve efficiency and productivity and can make goods and services more accessible to all. This certainly holds true for the transport sector and, in particular, the railway – the context of our research. However, the implementation of engineering technologies often comes with great uncertainties and can involve substantial amount of investment. Therefore, an economic understanding of the implementation and impacts of technologies is necessary but non-trivial: it involves a series of challenges which have surprisingly received little attention in the literature. This is particularly relevant to the railway industry where technical leaps may be very costly and where it accordingly is all the more necessary to provide both a financial rationale (for the infrastructure provider) as well as a wider economic motive for large investments.

Cost-Benefit Analysis (CBA) is a widely used tool to provide an economic assessment of transport projects. As part of the EC-funded NeTIRail-INFRA project, CBA has been applied for a range of railway engineering innovations which have been proposed and developed within the project. While CBA is frequently used for investment appraisals, it is well fit while less often used also for the evaluation of technical improvements.

Railway technology has been evolving over centuries and involves many complex elements and relationships: e.g. track and vehicle characteristics, varied track usage, vehicle-track interaction, different damage mechanisms, etc. Consequently, multiple maintenance and renewals techniques exist. Over time, better technologies have the potential to increase the life, quality and safety of assets, improve the understanding of the system (e.g. through better monitoring) and reduce the maintenance needs. While technology continues to develop, it is critical to fully understand the impacts of new technologies in economic terms.

7.1 Methodological challenges and contributions

Various challenges emerged in conducting CBA for the *innovative engineering technologies* that are in focus of the NeTIRail-INFRA project. Surprisingly, the financial and economic understanding of engineering processes can sometimes be vague, even within the core of the industry. Such processes can be very complex and surrounded by huge uncertainties (especially if a technology is new), so it is costly and not straightforward to gain full economic understanding. This was one of the outcomes of a Rail Structure Symposium organized at the University of Leeds with international experts in the railway, in the latest stages of the NeTIRail-INFRA project (January, 2018). Even worse, when some knowledge is acquired, there is a risk that it becomes confidential due to the competitive pressures exercised on the railway in certain countries. Since many railways are or have been funded with taxpayers' money, data transparency should be demanded.

In order to contribute to a robust economic understanding of the costs and benefits of various rail technologies, four different analytical techniques have been identified as part of the NeTIRail-INFRA research. They all have been implemented in the project, and it is worth noting they are complementary with each other. The four approaches are: i) on-site empirical observations, ii) econometric analysis, iii) interviews with experts and engineers, and iv) switching values approach

(DfT, 2017). Each of these techniques contributes to the generation of the necessary information and economic analysis outputs. It has proven useful to think of these different tools at the time of conducting the analysis, given that it was generally the case that some of these techniques/paths were not available for each particular case study.

We do not claim to develop any innovative approach to do a CBA. Instead our methodological contribution is two-fold: a) to highlight the importance of doing economic evaluation for technologies and the difficulties and barriers that practitioners often encounter, and b) to indicate alternative ways of obtaining the necessary inputs and overcoming the challenges. While the research and the discussion is framed around the railway industry, some of the challenges also apply to different sectors, within and outside transportation.

One of the key barriers to evaluation includes the challenge of obtaining information on the costs of the current (Do Minimum) approach, particularly in respect of individual lines and for specific assets. This is partly an issue of data availability but also accessibility and it may be that in future projects a specific data partner / manager, working within a railway with the specific task of accessing rail company information on costs and other metrics, would advance the economic analysis.

7.2 Overall CBA results for all innovations

While the overview of each independent CBA was provided at the end of each sub-section, there are several take-away messages that emanate from looking at the overall results of the different analyses. This is the aim of this final section.

First, we have seen how the status quo of any railway in terms of operation, inspection, maintenance and renewals is never fixed, and technology can help to improve the existing situation to save resources and/or improve quality (e.g. safety, reliability, etc.). Understanding the current situation is therefore essential to understand what elements in the system can or should be altered to move forward.

Secondly, our analyses show that achieving life cycle cost savings and improvements in quality can sometimes be achieved with very low or even no upfront monetary investments. This reflects one of the initial objectives of NeTIRail-INFRA, which was to develop affordable improvements for railways that would normally struggle to innovate. For instance, observing the way in which switches and crossing (S&C) are currently assembled and installed led to rethinking of the current practices, in a way that could help Infrastructure Managers to make a much more efficient employment of the workers and use of track at literally no monetary cost.

Another example is the use of new techniques for monitoring the quality of both the provision of electricity and the quality of tracks and structures. Newly developed monitoring devices can be as cheap as a smartphone and can generate very valuable information to IMs and operators. If used adequately, the information can promote a more preventative maintenance and renewals strategy that would save substantial amounts of resources to the railway and would improve passengers' experience, e.g. by avoiding failure-related delays.

Thirdly, even when a technology has a substantial financial cost upfront (e.g. the powerful ABA system for track monitoring), the potential benefits can be very large. This highlights the importance of allowing a good system of incentives in the industry that facilitates investments in innovation where the effects are in the long-term.

Finally, the economic analysis of technological advances in specific elements of the system, such as transition zones or the electrification of lines, have highlighted that sometimes the necessary knowledge might not exist at the level of detail that would enable IMs to make optimal choices. For example, even though it seems to be widely understood that transition zones are more expensive to maintain than the straight line, there is little evidence on what the size of the additional cost is). Similarly, cheaper forms of electrification are possible, but not much is known about the potential associated maintenance costs of those (in principle cheaper) techniques. We have also tried to fill some gaps in the existing economic understanding of a wide range of railway infrastructure elements and in particular adopted econometric models to shed new light on the relationship between different technological approaches and costs.

8. References

Andrade, A.R. (2008) An integrative approach using separate LCC models for rail and ballast components (MSc thesis), Instituto Superior Técnico, Universidade Técnica de Lisboa, Lisbon, Portugal.

Atkins (2007) T633: Study on Further Electrification on the UK railway. Department for Transport. <http://www.railwaysarchive.co.uk/documents/RSSB_Electrification2007.pdf>.

Atkins (2011) Whole Life Costing for Option Appraisal of Maintenance Schemes for Local Highway Authorities. <http://www.ukroadsliaisongroup.org/download.cfm/docid/D0FD6F76-E612-4435-A65E97F7E5E1FE92/version/7CC53D65-8291-400C-9EE07F4B0344A657>.

Barrow, K. (2017) SNCF to renew Paris RER Line C catenary. International Railway Journal. < http://www.railjournal.com/index.php/commuter-rail/sncf-to-renew-paris-rer-line-b-catenary.html>.

Barry, S. (2014) South Wales rail electrification scheme finally gets the go-ahead with a £230m funding package. Wales Online. https://www.walesonline.co.uk/news/wales-news/south-wales-rail-electrification-scheme-8146631.

Beck, A., Bente, H. and Schilling, M. (2013). Railway Efficiency – An Overview and a Look at Opportunities for Improvement. International Transport Forum Discussion Paper No. 2013-12

Clark, R. (2015) Cost of South Wales rail electrification 'four times higher' than last comparable major UK project. Wales Online. https://www.walesonline.co.uk/news/wales-news/cost-south-wales-rail-electrification-9939776.

Comptroller and Auditor Genera (2016) Modernising the Great Western railway. Department for Transport and Network Rail.

Department for Transport (2017). Value for Money Framework.

Duque, O., Zorita, A.L., García-Escudero, L.A., Fernández, M.A. (2009) Criticality determination based on failure records for decision-making in the overhead contact line system. Proceedings of the Institution of Mechanical Engineers Part F: Journal of Rail and Rapid Transit, 223 (5), pp. 485-494.

Ho, T.K., Chi, Y.L., Ferreira, L., Leung, K.K., Siu, L.K. (2006) Evaluation of maintenance schedules on railway traction power systems. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 220(2), pp. 91-102.

Keen, P., Phillpotts, R. (2010) Low Cost Electrification for Branch Lines. Department for Transport and DeltaRail Group Limited.

Kilsby, P., Remenyte-Prescott, R., Andrews, J.D. (2016) Modelling asset management of railway overhead line equipment. In: 9th IMA International Conference on Modelling in Industrial Maintenance and Reliability (MIMAR), 12-14 July 2016, London, UK.

Kirkwood, L., Giuntini, L., Shehab, E., Baguley, P. (2016). Development of a Whole Life Cycle cost model for electrification options on the UK rail system. Procedia CIRP, 47, pp.1-5.

Nellthorp, J. et al. (2015), *SUSTRAIL D5.2: Economic benefit final report,* SUSTRAIL (The sustainable freight railway: Designing the freight vehicle – track system for higher delivered tonnage with improved availability at reduced cost), EU 7th Framework Programme, Grant # 265740 FP7 - THEME [SST.2010.5.2-2.].

Nellthorp, J. et al. (2013), *SUSTRAIL D5.5: Interim Business Case Synthesis Report to Guide WP3 and WP4*, SUSTRAIL (The sustainable freight railway: Designing the freight vehicle – track system for higher delivered tonnage with improved availability at reduced cost), EU 7th Framework Programme, Grant # 265740 FP7 - THEME [SST.2010.5.2-2.].

NeTIRail-INFRA Deliverable 1.1. Report on selection of case studies.

NeTIRail-INFRA Deliverable 1.2. Database of economic data on case study lines

NeTIRail-INFRA Deliverable 2.1. Analysis of “big data”: geospatial analysis of costs, drivers of failure and life of track infrastructure.

NeTIRail-INFRA Deliverable D2.4. Application of lean and automotive industry techniques to produce a step change in railway S&C life and costs

NeTIRail-INFRA Deliverable D2.5. Corrugation reduction strategies for NeTIRail-INFRA track types, with estimates of costs and benefits.

NeTIRail-INFRA Deliverable 2.7. Lubrication Systems and Data Available, With Estimates of Costs and Benefits.

NeTIRail-INFRA Deliverable D2.10 Cost effective transition zone design tailored to line type and traffic

NeTIRail-INFRA Deliverable D3.2 Analysis of “big data”: tailoring overhead line infrastructure specification and needs through geospatial analysis of duty and life of equipment.

NeTIRail-INFRA Deliverable D3.5 Tailored combinations of wire tension, pantograph collector strip material and upload force for optimum performance.

NeTIRail-INFRA Deliverable D4.2. Low cost track based monitoring modules for plain line and S&C.

NeTIRail-INFRA Deliverable D4.4: Track and ride quality monitoring technology based on train-borne measurements in standard vehicles.

NeTIRail-INFRA Deliverable D4.6: Low cost smartphone based track and ride quality monitoring technology.

NeTIRail-INFRA Deliverable 5.1. Societal and legal effects of transport decision: Stakeholder analysis.

NeTIRail-INFRA 5.2. Perception of different service options: User study and data analysis.

Network Rail (2009) Network RUS: Electrification Strategy. Strategy documents collection. http://www.railwaysarchive.co.uk/docsummary.php?docID=3135.

Reddy, V., Chattopadhyay, G., Larsson-Kråik, P. O., & Hargreaves, D. J. (2007). Modelling and analysis of rail maintenance cost. International Journal of Production Economics, 105(2), 475-482.

Shing, A.W., Wong, P.P.L. (2008) Wear of pantograph collector strips. Proceedings of the Institution of Mechanical Engineers Part F: Journal of Rail and Rapid Transport, 222, pp. 169-176.

The Telegraph (2009) Electrified rail network: the benefits. http://www.telegraph.co.uk/news/uknews/road-and-rail-transport/5892821/Electrified-rail-network-the-benefits.html.

Appendix A

Railway Economics and Engineering; making informed decisions on railway maintenance and renewals

Jan-Eric Nilsson

Kristofer Odolinski

Both at the Swedish National Road and Traffic Research Institute (VTI)

For contact use full.name@vti.se

Draft: 2018-03-08

Abstract: Economic appraisal is widely used for providing an understanding of the cost and benefits of infrastructure projects. This paper applies the Benefit Cost Analysis technique to a less common topic, namely the identification of technical improvements that would also provide economic logic, i.e. improvements that are conceivable innovations in view of being financially and/or economically motivated. The improvements analysed in the paper concern fastening systems and the design of transition zones between bridges or tunnels and straight line. The impacts of the improvements are estimated, using econometric techniques on Swedish data. The quantitative results comprise an important input in the Benefit Cost Analysis of these technical improvements. The next (and final) step is to include their impact on train delays.

This work is part of the NeTIRAIL-INFRA project, which is funded from the European Union’s Horizon 2020 research and innovation programme under grant agreement NO 636237.

1. Introduction

Over time, and because of use, the quality of railway tracks deteriorates and require maintenance to retain usability. For a given degree of usage (no. of tons etc.) and with the passage of time, different designs of railway investment and renewal activities, and different choices of super structure (sleepers, the fastening system and rails), generate different patterns of deterioration and require more or less maintenance. For this reason, sections of the railway network that is expected to be used by many trains, by trains at high speeds and/or by very heavy trains are built using more robust equipment. This includes rails with high specific weight, switches that can be passed at high speeds, etc. Since robust equipment is more expensive than weak installations, the economic challenge is to establish when it is warranted to increase current spending on highly qualitative equipment to optimize life cycle maintenance costs and the risk for failures and train disturbances because of equipment that works more or less well.

This trade-off is well-known in principle but less often analysed and used in actual practice. This paper seeks to fill this gap for two situations where the optimal level of track quality is to be selected. One concerns the choice between different types of track fastening systems, and the other the design of transition zones between bridges or tunnels and the straight line. While the principal nature of life-cycle cost optimization is well known, the contribution of the paper is to demonstrate how a well-designed data base with information not only about track characteristics and traffic but also about maintenance costs and ideally about the impact on the risk for train delays of a failing infrastructure can be used in practice.

Two different types of decisions related to track maintenance and renewal are considered.

The fastening system: Different types of clips for tying a rail to a sleeper may require different levels of maintenance. Two types of data analyses will seek to provide input for quantification of this hypothesis. One approach addresses the difference in maintenance costs for tracks where different types of fastening systems have been inserted. The second approach looks in more detail to a particular type of maintenance activity, namely rail grinding. This analysis makes it feasible to establish if different fastening systems generate different quantities of grinding. Quantification of a (significant) effect will facilitate the choice of fastening system to use when tracks are to be rehabilitated.

Design of transition zones: A transition zone is the section of tracks between the straight line and a fixed installation. The interface between the stiff sub-structure in a tunnel or on a bridge and the less resilient sub-structure of the straight line which is built on macadam and other softer materials generates extra wear. Even a minor level difference in the joint between rails that rest on sub-structures with different stiffness, may trigger a negative, self-enforcing spiral that gradually increases the level between the two and depresses the sleepers on the softer line sub-structure. To prevent this from happening, transition zones require more maintenance than the straight line. These zones can, however, be reinforced by for example having a shorter distance between the sleepers, using a stronger type of clip, etc.

Two types of analyses are applied for addressing whether a major intervention on these zones can be motivated by a reduction of maintenance costs. One is related to the comparison of maintenance costs on train sections with different numbers of bridges and tunnels; by definition, each of these structures have two transition zones. A complementary data analysis is feasible since there are also different types of transition zones that have been installed. This means that it is possible to compare costs for different zone designs. Moreover, we also test the impact of transition zones on the level of grinding and track alignment activities.

2. Method

Two different methods are used to generate information about maintenance, one based on a cost model and another on models for grinding of rails and tamping, activities implemented to remedy track corrugation and poor track geometry, respectively.

The cost model: Let C represent maintenance cost, Q is traffic and $\boldsymbol{X}$ is a vector of infrastructure characteristics such as line-speed, switch length and type of clips. The cost model is

$$C = f(Q, \boldsymbol{X}), \tag{1}$$

For this evaluation, we wish to establish a relationship between different types of clips and maintenance costs. To do this, we need to specify a functional form. The double-log specification is common in the literature addressing rail infrastructure costs (see for example Munduch et al. 2002, Link et al. 2008, Wheat and Smith 2008, Smith and Wheat 2012, Odolinski and Nilsson 2017).[9] However, as there are many different types of clips, of which some were introduced quite recently into the Swedish railway network, many observations of clips have a zero value, for instance for all years before introduction. With a logarithmic transformation, observations would be lost. To avoid this, the variables for clips are expressed as shares of total clip length.

---

[9] Agents (in maintenance production) are more likely to have the same reactions to relative changes compered to absolute changes, and a logarithmic transformation of the variables can reduce skewness and heteroscedasticity (Heij et al. 2004).

Considering the evaluation of the effects on costs of two types of fastening systems (clip type A and type B), the (Cobb-Douglas) specification is

$$lnC_{it} = \alpha_i + \beta_1 ClipA_{it} + \beta_2 ClipB_{it} + \beta_2 lnQ + \beta_k \sum_{k=3}^{K} lnX_{kit} + \varepsilon_{it}, \qquad (2)$$

where i indicates track section (to be further described in the data section) and t indicates year. $ClipA_{it}$ and $ClipB_{it}$ indicates the number of clips on each track section i in year t. The analysis result in parameter estimates, and the null hypothesis $\hat{\beta}_1 = \hat{\beta}_2$ is tested against the alternative hypothesis $\hat{\beta}_1 \neq \hat{\beta}_2$. If the null hypothesis is rejected and if $\hat{\beta}_1 > \hat{\beta}_2$, the conclusion is that a higher proportion of clip A on a track section makes it necessary to undertake more maintenance, i.e. costs are higher.

The alternative method for evaluating the different clips and their impact on maintenance is more indirect. Specifically, maintenance inter alia includes the grinding of the surface of the rail in order to remedy corrugation. The purpose of the model analysis is to assess by how much the extent and ultimately the costs for grinding is affected by using different fastening systems. Le G be the length (no. of meters) of rail grinded during a period.

$$G = f(Q, \boldsymbol{X}), \qquad (3)$$

The methodological problem is that this maintenance activity is not performed each year on each track section, which implies that it has many zeroes each year. Once some of the track length of a section is grinded, the observation of length is, however, continuous, making a corner solution model relevant, where the zero values represent the corner solutions (Wooldridge 2002). The standard Tobit model is one of the corner solution models that can be applied to our dataset.[10] Following Greene (2012), we express the model as

$$G_i^* = Q_i'\beta_q + \boldsymbol{X_i'\beta_x} + \varepsilon_i,$$

$$G_i = 0 \; if \; G_i^* \leq 0,$$

$$G_i = G_i^* \; if \; G_i^* > 0. \qquad (4)$$

Considering that our dependent variable contains “genuine” zeroes (making the corner solution approach appropriate), we need to transform these when estimating the model in log form. We find the minimum log value of the dependent variable and set the missing observations infinitesimally below the minimum value (see Cameron and Trivedi 2009, p. 532).

---

[10] Other examples are the model proposed by Cragg (1971) and the Heckit model (see for example Dow and Norton 2003).

For the evaluation of transition zones, we specify a cost model in which we use information about the number of bridges and tunnels on each track unit. The idea here is to use total maintenance costs on each track section and regress on the frequency of bridges and tunnels, while controlling for other cost drivers. An approach for understanding the impact of transition zone reinforcement on maintenance costs is to use information about slab tracks. This is so since the transition from slab track to straight line always is reinforced according to rail engineers at *Trafikverket*. Prior to 2007, there were no installations with slab track. Then, starting with five slab track bridges in 2007, this number increased over the years; as of 2016 there were 19 bridges with slab track. For the sections that have slab track bridges, these bridges comprise between 2 and 100 per cent of all bridges on each segment. This makes it possible to use the standard regression model as a means for identifying the impact of slab tracks/reinforcements on maintenance costs.

In the alternative (indirect) approach, we use information about where grinding and (major) tamping activities have been implemented (costs for grinding and tamping on each track section is available for each year but they cannot be completely isolated in the maintenance cost data). Again, since information about the length of grinded rails and tamped tracks includes lots of zeros (no grinding or tamping that year), it is relevant to use corner solution models. Two models with different outcome (dependent) variables are therefore estimated using the Tobit model: 1) grinded tracks; and 2) tamped tracks.

Considering that most segments or track sections do not have a bridge with slab track, we estimate the cost model and the corner solution models using a variable for the share of structures that are reinforced. As the corner solution models are estimated with random effects, we use a dummy variable for all segments that sometime during the period 1999-2016 have a structure with slab track, as well as a dummy for all segments with a "normal" structure. In that way, we control for any segment-specific effects, so that they are not confounded with the impact from reinforced transition zones (note that these segment-specific effects are controlled for with a fixed effects (within) estimator, which is used in the cost model).

3. Data

Information about maintenance costs (first row in Table 1), the infrastructure characteristics, traffic as well as some maintenance activities has been collected from the Swedish Transport Administration (*Trafikverket*). Information on the infrastructure characteristics and maintenance activities (track grinding and tamping) is available at a more detailed level than traffic and cost data. Specifically, this information is at the so-called track segment level, comprising about 2500 observations each year between 1999 and 2016, while data available at the track section level comprise about 200 observations during 1999-2016; cost data is however only available for years 1999 to 2014. Hence, when maintenance cost is used as the dependent variable, it is necessary to aggregate the infrastructure characteristics to the track section level and to restrict the analysis to the 1999-2014 period. This is not the case when the purpose is to consider grinding or tamping since the length of track that has been given either type of treatment is the dependent variable in the corner solution models. However, we then need to use the more aggregate traffic volumes, which are averages at the track section level. Note that while information is available about the extent of grinding and tamping, the information about costs cannot be isolated for the two activities.

The knowledge about technical aspects of the infrastructure is rich. It includes information on track length, the quality class (line speed), average rail age and average rail weight, switch length, track length of grinded rails and of tamped track. Except for the number of bridges and tunnels, information is also available about their length. This also includes information on the transition zone characteristics, such as rail weight, type of sleepers and clips etc. Traffic is expressed as ton density (ton-km/route-km). A set of dummy variables indicate which regional unit within *Trafikverket* is responsible for the respective track sections (these time-invariant variables are dropped from the fixed effects estimations, but included in the Tobit (random effects) regression). From previous work with this data (Odolinski and Smith 2016), it is also clear that the year when a track section first was subject to competitive tendering is important for understanding the cost structure; the exposure to competition was gradual, starting in 2002. Descriptive statistics for track sections are provided in Tables 1 to 3, while the corresponding tables for segments is presented in the appendix. Note that there are a varying number of observations available for some of the variables, as indicated in Table 1.

Table 1 – Descriptive statistics, track sections: costs, traffic and infrastructure characteristics, 1999-2014

	Obs.	Mean	St. dev.	Min	Max
MaintC *(million SEK, 2014 prices)*	3 066	11.11	13. 88	0.01	209.22
Ttden *(train-km/route-km)*	3 066	17 102	21 342	0.2	192 475
TGTden *(ton-km/route-km), million*	3 066	7.60	8.44	15.8	65.85
Track_l *(meters)*	3 066	70 211	54 936	1473	299 154
Rail_age *(average age, years)*	3 032	21	11	1	96
Rail_w *(average weight, kg)*	3 066	51	5	32	60
Qualave *(average quality class; linespeed)*	2 955	2	1	0	5
Switch_l *(meters)*	3 019	1 709	1 691	29	14 393
ConcSleep_l *(track_l, meters)*	3 066	43 328	49 489	0	281 124
WoodSleep *(track_l, meters)*	3 066	22 053	30 686	0	176 928
SlabSleep *(track_l, meters)*	3 066	5	89	0	2 050
Unknw_sleeper *(track_l, meters)*	3 066	125	983	0	40 849
Bridge_l *(track_l, meters)*	3 066	708	1 315	0	15 412
Tunnel_l *(track_l, meters)*	3 066	477	1 889	0	17 897
Struct_l *(tracl_l, meters)*	3 066	1 186	2 929	0	24 464
Tunnel_no.	3 066	1.29	4.71	0	44
Bridge_no.	3 066	26	30	0	224
Struct_no.	3 066	28	32	0	267
ReinfStruct_no. *(Struct_no. with reinforced transition zones)*	3 066	0.03	0.38	0	9
D.Reinf_i *(dummy, sections with reinforced transition zone some year(s) during 1999-2014)*	3 066	0.04	0.20	0	1
ReinStruct_no._share *(share of structures with reinforced transition zones)*	3 066	0.00	0.01	0	0.5
Region_west	3 066	0.17	0.38	0	1
Region_north	3 066	0.13	0.33	0	1
Region_central	3 066	0.18	0.39	0	1
Region_south	3 066	0.27	0.44	0	1
Region_east	3 066	0.25	0.43	0	1
Ctend *(dummy when tendered in competition)*	3 066	0.47	0.50	0	1
Mixtend *(dummy for years with transition between tendered and not tendered in competition)*	3 066	0.06	0.24	0	1

Three types of sleepers are used. During 1999-2014 (the period which the cost model is based on), about two thirds of all sleepers were concrete or slab track, the rest being wooden (either hardwood or pine) or unknown; cf. Table 2. It should be noted that the type of sleeper does not automatically establish whether the line has slab track or not. Moreover, most track sections have a mix of concrete and wooden sleepers. For example, only 100 out of 216 sections have concrete sleepers comprising more than 75 per cent of all sleepers while 116 sections have a more even mix of concrete and wooden sleepers.

Table 2 – List of sleepers installed on the Swedish railway network 1999-2014 (3066 obs.)

Variable	Explanation	Share of total amount of sleepers installed, average 1999-2014
A22	Concrete with fast clip, max axle load 35 tons	0.48%
B	Concrete sleeper	21.83%
B101	Concrete, "two blocks", type 101	0.47%
B2.3	Concrete, monolith, 2.3 metres	2.33%
B2.3H	Concrete, monolith, 2.3 metres, hollowed for "protection rail"	0.02%
B2.5	Concrete, monolith, 2.5 metres	34.03%
B2.5F	Concrete, monolith, 2.5 metres, enhanced	1.18%
B2.5H	Concrete, monolith, 2.5 metres, hollowed for "protection rail"	0.01%
H	Hardwood, beech or oak	5.29%
T	Pine	34.10%
TBRO	Wooden sleeper for steel bridges	0.02%
Unknown	Unknown sleeper	0.24%

Each sleeper category has its own design of clips. A list of the different clips is provided in Table 3 while Appendix A provides a technical description of the different types.

Table 3 – Descriptive statistics, track sections: clips 1999-2014 (3066 obs.)

		Track length on sections (meters)				*Share of track length on sections*			
Variable	Definition	Mean	St. dev.	Min	Max	Mean	St. dev.	Min	Max
	For concrete sleepers								
C1	"Fist clip", only used in Sweden	1 856	7 327	0	93 339	0.03	0.10	0.00	0.97
C2	Hambo clip, Swedish construction	5 492	17 285	0	174 230	0.09	0.20	0.00	0.99
C3	Base plates/Clamping plates	0	8	0	387	0.00	0.00	0.00	0.05
C4	E-clip, pandrol	34 473	43 991	0	232 570	0.47	0.38	0.00	1.00
C5	E-clip, deep-post, pandrol	2	117	0	6 459	0.00	0.00	0.00	0.04
C6	E-clip plus, pandrol	5	65	0	1 316	0.00	0.00	0.00	0.04
C7	Fast clip, pandrol	1 314	5 845	0	70 057	0.02	0.10	0.00	1.00
	For slab track								
S1	VIPA 5, for slabtrack (Pandrol)	0	3	0	184	0.00	0.00	0.00	0.00
S2	VIPA 6, for slabtrack (Pandrol)	0	2	0	132	0.00	0.00	0.00	0.00
S3	Pandrol VIPA F1	1	14	0	418	0.00	0.00	0.00	0.01
S4	Pandrol VIPA SP	1	22	0	902	0.00	0.00	0.00	0.01
S5	Vossloh Cogifer (for turnouts)	4	75	0	1 561	0.00	0.00	0.00	0.01
	For wooden sleepers								
W1	Spring spike system	634	3 255	0	27 251	0.01	0.07	0.00	0.95
W2	Hey-back	7 522	15 940	0	131 782	0.13	0.22	0.00	1.00
W3	Spike, "locking nail"	211	1 144	0	14 455	0.01	0.06	0.00	1.00
W4	Spike	1 647	5 305	0	61 734	0.04	0.12	0.00	1.00
W5	Spike with base plate	11 811	26 193	0	175 879	0.20	0.31	0.00	1.00
W6	Screw system (for turnouts)	88	432	0	7 154	0.00	0.03	0.00	0.95
U1	Unknown clip	322	1 726	0	40 849	0.01	0.03	0.00	1.00

As indicated above, the analysis will be based on information about the share of track length with the different types of clips at each section.

4. Results: The impact on maintenance of using different types of fastenings

4.1 The impact on costs

Since the variables for clips and sleepers are expressed as shares of total track length, one of the clip or sleeper types are required as a baseline. We use the clips for wooden sleepers as the baseline in Model 1a and clips for concrete sleepers are the baseline in Model 1b. Although dummy variables for each year (2000-2014) are included in the estimations, the parameter estimates are not included in table 5 for expositional simplicity. It can, however, be noted that they are jointly significant (F(1, 215)=19.27, Prob>F = 0.000).

Table 4 – The impact on costs of traffic and technical variables. Model 1a (baseline=clips for wooden sleepers) and Model 1b (baseline=clips for concrete sleepers), Fixed effects (2912 obs.)

	Model 1a		Model 1b	
	Coef.	Rob. Std. Err.	Coef.	Rob. Std. Err.
Cons.	13.12067***	0.753939	12.7554***	0.7546
ln(Tgtden)	0.0985**	0.0388	0.1016**	0.0394
ln(Switch_l)	0.2254***	0.0587	0.2151***	0.0588
ln(Qualave)	-0.4665***	0.1635	-0.4506***	0.1671
Clip C1	-0.4168*	0.2410	-	-
Clip C2	-0.1174	0.2843	-	-
Clip C3	-29.0508***	2.5250	-	-
Clip C4	-0.3558***	0.0971	-	-
Clip C5	10.8794	7.3239	-	-
Clip C6	3.7194	2.4170	-	-
Clip C7	-0.8951***	0.2242	-	-
Clip W1	-	-	0.7442*	0.3964
Clip W2	-	-	0.5024***	0.1332
Clip W3	-	-	-0.0129	1.7248
Clip W4	-	-	0.7708	0.4786
Clip W5	-	-	0.3602**	0.1681
Clip W6	-	-	-4.6998**	2.3124
Clips S1-S4	62.2951**	26.7930	61.2642**	24.6919
Clip S5	25.4163***	3.5026	26.4389***	3.4109
Clip U1	-0.2124	0.2829	0.3558	0.2834
Mixtend	-0.0124	0.0398	-0.0139	0.0399
Ctend	-0.1351***	0.0451	-0.1291***	0.0453
Year dummies 2000-2014[a]	Yes		Yes	

***, **, *: Significance at 1%, 5%, 10% level,
[a] Jointly significant (F(1, 215)=19.27, Prob>F = 0.000)

Since the focus is on concrete sleepers, Model 1a is relevant for the present analysis. Here, the (significant) coefficients refer to types of fastenings that are more (positive) or less (negative sign) costly to maintain than the average for clips installed on wooden sleepers.

The two coefficients for slab track (clips S1-S4 and clip S5) stand out for their large value, meaning that they are much more expensive to maintain than the average sleeper. These clips are used for turnouts (requires more maintenance compared to regular tracks), as well as for transition zones; this will be revisited as part of the analysis on transition zones in section 4.2.

The coefficients for the logged independent variables can be interpreted as elasticities. However, when evaluating the coefficients for the variables expressed as (unlogged) shares of track section length, it is necessary to transform the observation. Using $\frac{\Delta C}{C} = 100 \cdot [\exp(\hat{\beta}_k \Delta X_k) - 1]$, where $\hat{\beta}_k$ is the parameter estimate for variable X_k, gives us the percentage change (Δ) of the predicted maintenance costs (C) when variable X_k changes. For example, clip C7 is on average used for 2 percent of track section length (cf. table 4). Increasing the share of these clips so that it is used for 4 per cent of the track section length, implies ($100 \cdot [\exp(-0.8951 \cdot 0.02) - 1] = -1.774$) about 1.8 percent reduction in costs compared to the average clip for wooden sleepers, while increasing the share track section length of the C4 clip (estimate=-0.3558) with 0.02 implies about that costs shrink by 0.7 per cent (cf. Table 5). Here we can note that clip C7 is designed for being fastened and released with machines, while clip C4 requires manual work.

This information can be used for several thought experiments. Assume, for instance that there would be a switch to concrete sleepers using clip C7 on two percent of the (average) track section length using wooden sleepers. This would reduce maintenance costs with 1.77 per cent. If we instead make the corresponding switch to clip C4, maintenance cost would be reduced by 0.7 per cent. This can also be used for understanding what would happen if there was a switch from C4 to C7 clips on concrete sleepers, for instance when track renewal is still imminent. In that case, the annual maintenance costs would shrink by (1.77-0.7=) 1.07 per cent; the difference between clip-coefficients is statistically significant (F(1, 215)=5.26, Prob>0.023). Since the average maintenance cost on a track section is SEK 11.55 million (based on the estimation sample), this corresponds to an annual saving of SEK 123 089. Note that the 2 per cent switch of clips corresponds to almost 1.5 km of track renewal.

Table 5 – Percentage change in costs: clips for concrete sleepers (Model 1a)

Clip type	% change in costs due to 0.02 increase in share of clip	F-test if coefficient is different from C7-coefficient (β_{pfcC7})	Prob>F
C7	-1.774	-	-
C1	-0.830	5.06	0.026
C2	-0.234	4.93	0.027
C3	-44.067	126.32	0.000
C4	-0.709	5.26	0.023
C5	24.307	2.58	0.110
C6	7.722	3.66	0.057

Except for clip C5, Table 5 demonstrates that the differences between the coefficient for the C7 clip (-0.8951) and all the other coefficients for concrete sleeper clips are statistically significant.

4.2 The impact of clip types on grinding

While the previous model seeks to estimate the direct impact on maintenance costs by using different fastening systems, the corner solution model considers an indirect cost driver, i.e. the consequences of different explanatory variables for the extent of track grinding. The results from the corner solution models for grinded track meters are presented in Table 6. Clips for wooden sleepers constitute the baseline in Model 2a, while clips for concrete sleepers are the baseline in Model 2b.

Table 6 – The impact on the need for grinding of traffic and technical variables, Model 2a (baseline=clips for wooden sleepers) and Model 2b (baseline=clips for concrete sleepers), Tobit regression (41 676 obs.)

	Model 2a		*Model 2b*	
	Coef.	Std. Err.	Coef.	Std. Err.
Cons.	-11.2975***	1.4442	-11.1188***	1.4617
ln(tgtden)	0.5608***	0.0196	0.5319***	0.0209
ln(track_l)	0.1646***	0.0212	0.1646***	0.0212
ln(rail_w)	-0.8749**	0.3861	-0.7168*	0.3667
ln(Qualave)	0.1233*	0.0725	0.1526**	0.0722
Struct_no	0.0599***	0.0076	0.0570***	0.0076
Clip C1	0.5762**	0.2324	-	-
Clip C2	0.4059***	0.1347	-	-
Clip C3	7.2528	25.4897	-	-
Clip C4	0.3206***	0.1016	-	-
Clip C5	24.9329***	6.6669	-	-
Clip C6	-0.9826	1.6974	-	-
Clip C7	1.1700***	0.1835	-	-
Clip W1	-	-	-0.3781	0.3155
Clip W1	-	-	-0.1172	0.1167
Clip W1	-	-	-1.1456**	0.5306
Clip W1	-	-	0.1925	0.2133
Clip W1	-	-	-0.7125***	0.1174
Clip W1	-	-	0.0539	0.8890
Clip S1-S4	-2.3357	8.0031	-0.4129	7.9945
Clip S5	-1.5471	3.3552	-1.9663	3.3630
Region dummies (nth, ctr, sth, wes)[a]	Yes		Yes	
Year dummies 2000-2016[b]	Yes		Yes	

***, **, *: Significance at 1%, 5%, 10% level,
[a] Jointly significant (Model 2a: chi2(4)=784.79, Prob>chi2=0.000),
[b] Jointly significant (Model 2a: chi2(17)=2943.26, Prob>chi2=0.000; Model 2b: chi2(17)=3190.97, Prob>chi2=0.000)

We first note that both the extent of traffic (Tgtden), the length of tracks (Track_l), the weight of an average rail (rail_w) and line-speed (Qualave) are positive and statistically significant. The first two parameter estimates (elasticities) indicate by how much more traffic (gross tonnes) and longer track sections affect the need for grinding.

The track quality variable (Qualave) goes from 0 to 5 where the higher number indicates a line with lower permitted speeds as well as lower requirements on track geometry standard (which is corroborated by the estimation results for tamping in model 4; less tamping is performed on lines with low linespeeds/low requirements on track geometry). An explanation for the positive and significant estimate for Qualave is therefore that poor track geometry is associated with more corrugation or other types of rail damages that require grinding.

Turning to the estimates for the different clips, the coefficient for clip C7 indicates that this type of clip implies more grinding of rails compared to clips for wooden sleepers. In fact, the level of grinding is higher on tracks with this clip compared to most of the other clips for concrete sleepers, except for clip C3 and clip C5. The latter type of clip is designed for curved tracks and high axle loads. The significant and very high coefficient value indicates that the high axle loads associated with this type of clip makes it necessary to grind tracks intensely, not because of the clip per se but since it is used on curved track segments that carry heavy loads. This feature is not fully captured by our average ton density variable. The impact of heavy loads on the level of grinding might also explain the coefficient for clip C7, since it is used for tracks with a high maximum axle load (either 25 or 30 tons).

To evaluate the impact of the coefficients for clips, we use $\frac{\Delta G}{G} = 100 \cdot [\exp(\hat{\beta}_k \Delta X_k) - 1]$. In the same way as above, $\hat{\beta}_k$ is the parameter estimate for variable X_k, and the expression gives the percentage change of the predicted grinded track meters (*G*) when variable X_k changes. Thus, increasing the share of clip C7 from 2 per cent of the average track section length to 4 percent implies a ($100 \cdot [\exp(1.1700 \cdot 0.02) - 1]$=) 2.37 per cent increase in grinded track meters. This can be compared to the C4 clip where the corresponding switch would imply a ($100 \cdot [\exp(0.3206 \cdot 0.02) - 1]$=) 0.64 per cent increase in grinded track meters. The difference in impact between these clips (C7 and C4) is thus (2.3676-0.6433=) 1.72 per cent.

Since on average about 512 track meters are grinded per year on a segment, this means that a switch from the average wooden sleepers to clip C4 instead of clip C7 would result in a reduction of grinded tracks at (0.1724*512=) 88 meters per segment and year; the difference between the coefficients is statistically significant: chi2(1)=27.16, Prob>chi2=0.000). However, it was previously demonstrated that this would still result in higher maintenance costs (about SEK 123 089 according to the Model 1a results). This shows that it is important to consider more than one maintenance activity when comparing different fastening systems with respect to their impact on maintenance: while a shift from clip C7 to C4 would reduce track grinding it would increase the need for other maintenance activities and boost costs.

5. Transition zone design

A transition zone is the section of tracks between the straight line and a bridge or tunnel. These zones can be reinforced by for example having a shorter distance between the sleepers and/or using a stronger type of clip. Some tunnels and bridges have slab track installed while other use standard type sleepers and fastenings. Considering that structures with slab track is an indication of a structure with a transition zone, we can use that information to evaluate reinforced transition zones. On average, there are 28.3 structures on a section, while there are on average only 0.03 structures on a track section that have reinforced transition zones.

The use of Swedish cost data makes it possible to present some initial results regarding the cost impact of transition zones. With information on where clips for slab track are installed, we can compare reinforced with regular transition zones.

5.1 The impact of transition zones on maintenance costs

The previous section considered the impact of different types of fastening systems, not only on costs but also on the need for one particular type of maintenance activity, namely grinding. The impact on costs and grinding of transition zones is considered also in this section, but in addition, information about the extent of tamping is used to enhance our understanding of cost drivers.

5.2 The cost model[11]

The presence of tunnels and bridges on a rail section provides a first indication of the effect of transition zones on maintenance costs. The impact on costs of traffic and switch length is as expected and statistically significant (Table 7). A variable for the number of bridges and tunnels (Struct_no.) is also included and the parameter estimate is 0.1667 and statistically significant at the 5 per cent level. The estimate can be interpreted as an elasticity due to the double log-specification of the model. Increasing the number of structures on an average track section with 100 per cent will increase the maintenance costs with up to about 17 percent. Since the average maintenance cost in the estimation sample is SEK 11.38 million per track section and a 100 per cent increase in structures imply (28.3*2) 56.6 new transition zones on the average track section[12], the estimated annual extra cost per

---

[11] We considered using the same model for the two econometric analyses (see Table 6). However, that would mean losing 101 observations. However, we do not consider that there is omitted variable bias by using a model that excludes the variables in Table 6 (partly because we used fixed effects and also based on further testing).

[12] Each bridge or tunnel has two transition zones and there are on average 28.3 structures on a track section.

transition zone is about (0.17*11 380 000/56.6=) SEK 34 000. This is based on the overall costs for structures. Since not only the transition zone, but also other parts of the structures may require maintenance, this number provides an upper limit for the impact on costs if the number of transition zones would change or if each zone could be reinforced.

Table 7 - The impact on costs of traffic and technical variables. Model 3, Fixed effects (2978 obs.)

	Coef.	Rob. Std. Err.
Cons.	11.0436***	0.9720
ln(Tgtden)	0.1423***	0.0458
ln(Switch_l)	0.2393***	0.0877
ln(Struct_no)	0.1667**	0.0761
Reinstruct_no_share	-0.1581	0.3057
Woodsleep_share	0.3875***	0.0953
Slabsleep_share	27.9601***	6.2962
Mixtend	0.0144	0.0390
Ctend	-0.1034**	0.0511
Year dummies 2000-2014[a]	Yes	

***, **, *: Significance at 1%, 5%, 10% level,

[a] Jointly significant (F(15, 218)=17.05, Prob>F=0.000)

Table 7 also includes a variable for the share of structures that have reinforced transition zones (Reinstruct_no_share). The coefficient has the expected (negative) sign, indicating that transition zone reinforcement reduces maintenance costs. Even though this value is not statistically significant (p-value is 0.606)[13], the same type of equation as above is used for estimating the cost impact of strengthening a transition zone. The generic expression is $100 \cdot [\exp(\hat{\beta}_k \Delta X_k) - 1]$, where $\hat{\beta}_k$ is the parameter estimate for variable X_k (i.e. share of structures that are reinforced, where one structure corresponds to two reinforced transition zones). In this way, it is possible to illustrate the benefits of econometric analysis also on a detailed level. Since we expect to get access to information for another two years, and since transition zones seems to be gradually reinforced, it will be straightforward to update results.

In this case, the thought experiment means that all transition zones on the structures are reinforced; while there on average are 27.5 structures on each track section in the network (cf. Table 1), there are on average 28.28 structures in the estimation sample; of these, only 0.03 have reinforced transition zones. The thought experiment therefore corresponds to an increase of (28.25*2=) 56.5 reinforced transition zones on the average track section. The average share of transition zones that are reinforced

---

[13] Note that only about 1.1 per cent of all the observations in the regression have a reinforced transition zone.

is currently 0.063 per cent. Thus, the strengthening implies that the average value for the share of structures with reinforced zones increases from 0.00063 to 1 (i.e. with 0.9994). Using the estimated parameter implies a maintenance cost reduction with $(100 \cdot [\exp(-0.1581 \cdot 0.994) - 1] =)$ 14.6 per cent. Since the average maintenance cost is SEK 11.38 million, this reduction corresponds to SEK 1.66 million per year and about SEK 29 400 per transition zone and year.

This result is close to cost per transition zone (SEK 34 000) established above, indicating that the driving force behind structures being costlier than the straight line indeed seems to be the transition zones. “Seems” here refers to that the coefficient is not statistically significant.

5.3 The corner solution model

While Table 1 provided descriptive data about track sections, Table 9 in the appendix summarizes the same type of information at the track segment level. Since each track section on average comprises more than 12 track segments, we now have access to more detailed information compared to the analysis on costs. This enhances the statistical precision in our conclusions.

Table 9 establishes that there are 512 and 663 meters of tracks that on average are grinded and tamped, respectively, per year and per segment. The focus of our inquiry is to understand the consequences for the need for tamping and grinding when a transition zone is reinforced. Using a corner solution model, these results are presented in Table 8 where Model 4a refers to the impact on tamping and Model 4b the impact on track grinding. We use variables for the share of track length with a certain sleeper type instead of clip type. The variable for concrete sleepers must be dropped since it is almost perfectly correlated with the variable for wooden sleepers, i.e. concrete sleepers form the baseline for the sleeper type estimates.

The coefficient for the number of structures (Struct_no.) is positive and statistically significant in both models (p-value 0.000). This means that the presence of bridges and tunnels increases the need for both tamping and grinding. As this variable is not log-transformed while the dependent variable is, the percentage increase in tamped track meters (Model 4a) from one extra structure increases by $(100 \cdot [\exp(0.0876 \cdot 1) - 1] =)$ 9.15 per cent. The impact on grinding (Model 4b) is 0.0583, which implies that one extra structure leads to a $(100 \cdot [\exp(0.0583 \cdot 1) - 1] =)$ 6 per cent increase in grinded track meters.

When the share of reinforced transition zones increases, the need for tamping is reduced (reinstruct_no_share, is -5.8895, p-value 0.028). Transition zone reinforcement will, however, increase the need for grinding (reinstruct_no_share, is 3.4716, p-value 0.031).

It is feasible again to consider the impact of reinforcing transition zones on all structures, and to calculate the consequences for the two specific maintenance activities. The average value for the share of structures with reinforced zones then increases with 0.5685 (from 0.0005 to 0.5690). Such a change implies a decrease in tamped tracks with $(100 \cdot [\exp(-5.8895 \cdot 0.5685) - 1] =)$ 96.49 per cent (!). This can be compared to the impact of transition zones in general: considering that there are on average 2.3 structures without a reinforced transition zone on each segment (cf. Table 9), an increase with 100 per cent of such structures would result in a $(100 \cdot [\exp(0.0876 \cdot 2.3) - 1 =]$ 22.32 per cent increase of tamped tracks. Hence, the results suggest that the reinforced transition zones require less tamping than a regular line. However, these results should be interpreted with care, considering that a reduction in tamping with 96.5 per cent (due to the reinforcement of all transition zones) indicates that almost all tamping is made on non-reinforced transition zones.

Table 8 – The impact of external variable on two types of maintenance activities, Model 6, Tobit regression (41 676 obs.)

	Model 4a (tamping)		*Model 4b (grinding)*	
	Coef.	Std. Err.	Coef.	Std. Err.
Cons.	1.9155	2.6399	-12.0484***	1.4029
ln(tgtden)	0.6370***	0.0354	0.5588***	0.0196
ln(track_l)	0.9257***	0.0406	0.1657***	0.0212
ln(rail_w)	-6.3525***	0.6718	-0.5907*	0.3589
ln(qualave)	-1.4506***	0.1370	0.1315*	0.0725
Struct_no	0.0876***	0.0147	0.0583***	0.0076
D.reinf_i	0.7749	0.8354	-0.0531	0.4295
Reinstruct_no_share	-5.8895**	2.6720	3.4716**	1.6128
Slabsleep_share	1.4466	6.2254	-4.0071	3.3532
Woodsleep_share	0.3469**	0.1766	-0.3331***	0.0947
Region dummies (nth, ctr, sth, wst)[a]	Yes		Yes	
Year dummies 2000-2016[b]	Yes		Yes	

***, **, *: Significance at 1%, 5%, 10% level,
[a] Jointly significant (Model 4a: chi2(4)=252.31, Prob>chi2=0.000; Model 4b: Chi2(4)=771.72, Prob>chi2=0.000),
[b] Jointly significant (Model 4a: Chi2(17)=1516.77, Prob>chi2=0.000; Model 4b: Chi2(17)=3171.17, Prob>chi2=0.000)

6. Conclusion

A rail infrastructure manager seeks different ways to reduce costs, either production costs (maintenance and renewals) or costs for traffic disruptions (delay costs). Different technical solutions will have different impacts on these costs, which of course to a large extent depends on the differences in the production environment. The data used in this paper shows that the Swedish infrastructure manager have, for example, installed various fastening systems on the railway network. A way forward in reducing costs is to evaluate the effects of the different technical solutions currently used. When doing this, one needs to consider the heterogenous production environment of the railways.

This paper has provided quantitative assessments of the different fastening systems and transition zones on the Swedish railway infrastructure, using detailed data on costs, traffic, maintenance activities and infrastructure characteristics. Specifically, the estimation results are used to calculate the change in annual maintenance costs when switching from one clip to another, or when reinforcing a transition zone, while controlling for other factors such as traffic volume and line-speed.

The results provided are crucial for a Benefit Costs Analysis of different fastening systems and transition zones. However, to take appropriate, welfare improving action it is also necessary to consider the impact of track quality on train delays. This requires information on the number of delays caused by the infrastructure (and its different subsystems that the technical solution belongs to). This is an area for future research.

References

Andersson, M., Smith, A., Wikberg, Å., and Wheat, P. 2012. Estimating the marginal cost of railway track renewals using corner solution models. Transportation Research Part A, 46, 954-964.

Cameron, A.C., and Trivedi, P.K., 2009. Microeconometrics Using Stata. Stata Press, StataCorp LP.

Cragg, J., 1971. Some statistical models for limited dependent variables with application to the demand for durable goods. Econometrica, 39, 829-844.

Dow, W.H., and Norton, E.C., 2003. Choosing Between and Interpreting the Heckit and Two-Part Models for Corner Solutions. Health Services & Outcomes Research Methodology 4, 5-18.

Greene, W.H., 2012. Econometric Analysis. Seventh edition, international edition. Pearson Education Limited, Edinburgh Gate, Harlow.

Heij, C., de Boer, P., Franses, P.H., Kloek, T., van Dijk, H.K., 2004. Econometric Methods with Applications in Business and Economics. Oxford University Press Inc., New York.

Link, H., Stuhlehemmer, A., Haraldsson, M., Abrantes, P., Wheat, P., Iwnicki, S., Nash, C., Smith, A.S.J., 2008. CATRIN (Cost Allocation of TRansport INfrastructure cost). Deliverable D 1, Cost allocation Practices in European Transport Sector. VTI, Stockholm, March 2008.

Munduch, G., Pfister, A., Sögner, L., Siassny, A., 2002. Estimating Marginal Costs for the Austrian Railway System. Vienna University of Economics & B.A., Working Paper No. 78, February 2002.

Odolinski, K., and Smith, A.S.J., 2016. Assessing the cost impact of competitive tendering in rail infrastructure maintenance services: evidence from the Swedish Reforms (1999 to 2011). *Journal of Transport Economics and Policy,* 50(1), 93-112*.*

Odolinski, K., Nilsson, J-E., 2017. Estimating the marginal maintenance cost of rail infrastructure usage in Sweden; does more data make a difference? Economics of Transportation, 10, 8-17.

Smith A.S.J., Wheat P., 2012. Estimation of Cost Inefficiency in Panel Data Models with Firm Specific and Sub-Company Specific Effects. J. of Productivity Analysis, 37 (1), 27-40.

Trafikverket, 2015a. Råd – Spårkomponenter. Spårkomponenter Sliper och befästning. TDOK 2015:0052, Version 0.1, 2015-04-01. (In Swedish)

Trafikverket 2015b. BVH 825.10 – Slipning av räler och spårväxlar. TDOK 2014:0485.

Wheat, P., Smith, A.S.J., 2008. Assessing the Marginal Infrastructure Maintenance Wear and Tear Costs for Britain's Railway Network. J. of Transp. Economics and Policy. 42(2), 189-224.

Wooldridge, J.W., 2002. Econometric analysis of cross section and panel data. The MIT Press, Cambridge, Massachusetts, London, England.

Appendix B

Table 9 – Descriptive statistics, average per year per track segment (41 676 obs.)

Variable	Mean	St.dev.	Min	Max
Grinded_track_m *(meters)*	512	2 037	0	60 663
Tamped_track_m *(meters)*	663	1 808	0	29 747
TGTden *(ton-km/rout-km), million*	8.14	8.92	0.00	65.85
Track_l *(meters)*	5 895	5 845	3	67 532
Rail_age *(years)*	22	13	0	112
Rail_w *(kg)*	51	6	27	60
Qualave *(average quality class; linespeed)*	2	1	0	5
Switch_l *(meters)*	139	348	0	6 419
ConcSleep *(track_l, meters)*	3 620	4 727	0	33 670
WoodSleep *(track_l, meters)*	1 877	4 052	0	51 291
SlabSleep *(track_l, meters)*	1	25	0	1 741
ConcSleep_share	0.61	0.44	0.00	1.00
WoodSleep_share	0.38	0.44	0.00	1.00
SlabSleep_share	0.00	0.01	0.00	0.50
Bridge_l *(track_l, meters)*	61	310	0	15 412
Tunnel_l *(track_l, meters)*	42	373	0	17 443
Struct_l *(track_l, meters)*	102	510	0	17 479
Bridge_no.	2	4	0	108
Tunnel_no.	0	1	0	27
Struct_no.	2.3	4	0	112
ReinfStruct_no. *(Struct_no. with reinforced transition zones)*	0.003	0.078	0	5
D.Reinf_i *(dummy, sections with reinforced transition zone some year(s) during 1999-2016)*	0.006	0.074	0	1
ReinStruct_no._share *(share of structures with reinforced transition zones)*	0.0005	0.015	0	1
Region_west	0.22	0.42	0	1
Region_north	0.14	0.34	0	1
Region_central	0.21	0.41	0	1
Region_south	0.20	0.40	0	1
Region_east	0.19	0.39	0	1

Table 10 – Descriptive statistics (41 676 obs.)

		Track length on segments (meters)				*Share of track length on segments*			
Variable	Definition	Mean	St.dev.	Min	Max	Mean	St.dev.	Min	Max
	For concrete sleepers	139	965	0	22 425	0.02	0.12	0.00	1.00
C1	"Fist clip", only used in Sweden	445	1 744	0	18 901	0.08	0.24	0.00	1.00
C2	Hambo clip, Swedish construction	0	6	0	517	0.00	0.00	0.00	0.07
C3	Base plates/Clamping plates	2 857	4 340	0	32 720	0.48	0.44	0.00	1.00
C4	E-clip, pandrol	1	18	0	1 070	0.00	0.00	0.00	0.27
C5	E-clip, deep-post, pandrol	1	20	0	1 316	0.00	0.01	0.00	0.79
C6	E-clip plus, pandrol	162	1 023	0	23 859	0.03	0.15	0.00	1.00
C7	Fast clip, pandrol	139	965	0	22 425	0.02	0.12	0.00	1.00
	For slab track								
S1	VIPA 5, for slabtrack (Pandrol)	0.0	1.6	0.0	184	0.00	0.00	0.00	0.03
S2	VIPA 6, for slabtrack (Pandrol)	0.0	1.1	0.0	132	0.00	0.00	0.00	0.02
S3	Pandrol VIPA F1	0.1	3.2	0.0	316	0.00	0.00	0.00	0.31
S4	Pandrol VIPA SP	0.1	5.2	0.0	691	0.00	0.00	0.00	0.07
S5	Vossloh Cogifer (for turnouts)	0.4	21.7	0.0	1 465	0.00	0.01	0.00	0.50
	For wooden sleepers								
W1	Spring spike system	50	566	0	14 229	0.01	0.08	0.00	1.00
W2	Hey-back	593	1 872	0	29 780	0.12	0.26	0.00	1.00
W3	Spike, "locking nail"	14	175	0	10 357	0.01	0.05	0.00	1.00
W4	Spike	150	1 124	0	38 112	0.03	0.14	0.00	1.00
W5	Spike with base plate	1 051	3 269	0	51 262	0.21	0.37	0.00	1.00
W6	Screw system (for turnouts)	7	104	0	7 154	0.00	0.03	0.00	1.00
U1	Unknown clip	29	318	0	16 624	0.01	0.05	0.00	1.00

Appendix C

Description of types of clips

The “**Fist clip**” used to be the standard clip for concrete sleepers (see Figure 1), with a 4.8 mm rubber pad installed between the rail and the sleeper. This clip was installed on about 2.5 million sleepers during the years 1957 to 1976. However, a few weaknesses with this clip have been discovered, such as rusts and problems with an expanding insulation material creating cracks in the sleepers. These problems have eventually caused speed restrictions and immediate replacements of clips and sleepers. Therefore, the Fist clip has gradually been replaced on the railway network.

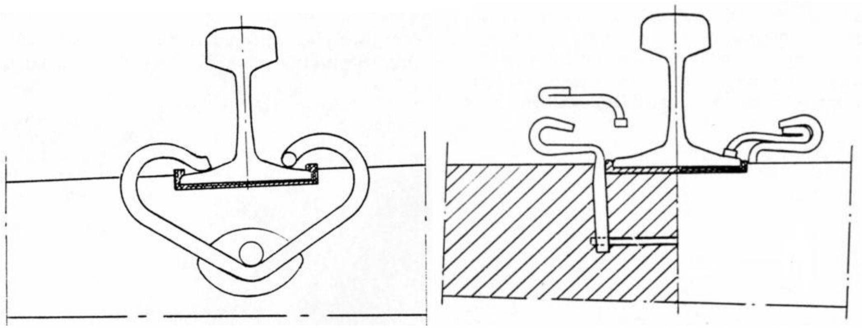


Figure 1 – Fist clip and Hambo clip (Trafikverket 2015a)

The **Hambo clip** is a Swedish construction by Hammerin and Borup (see Figure 1), with a 5.5 mm plastic pad. The shoulder of the clip (cast into the sleeper) is the weakest part and a replacement of these shoulders have therefore been developed.

There are several types of Pandrol clips on the railway network (see Figures 2 and 3). One group is called **E-clips**, which originally was installed with a 5.5 mm plastic pad. Later on (beginning in 1990/1991), a 10mm pad has been used together with a new type of shoulder. The Pandrol **Deep-Post** uses a 10mm pad and is designed for curved tracks and high axle loads. The **E-clip plus** is the strongest Pandrol clip and also comes with a 10mm pad. The Pandrol **Fast clip** has become the standard clip in the Swedish railway network, and was introduced in 2008. It is used for track with either 25 or 30 tons maximum axle load.

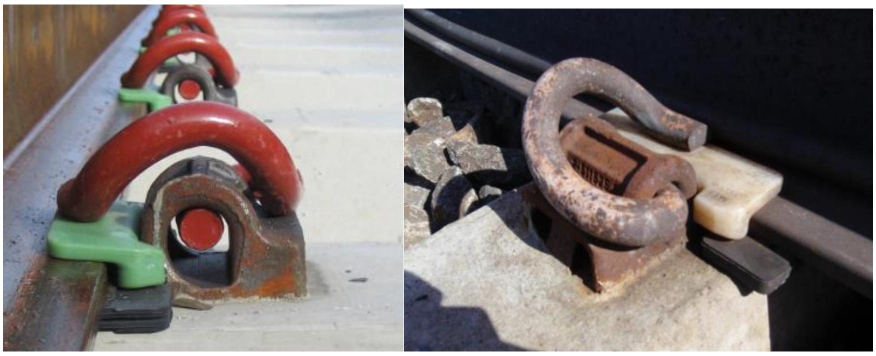


Figure 2 – Pandrol E-clip (1817) and Deep-Post (Trafikverket 2015a)

Figure 3 – Pandrol e-Plus and Fast clip (Trafikverket 2015a)

Moreover, there are a set of Pandrol clips for slab track, as well as the Vossloh DFF fastening system (see Figure 4). These clips are not very common on the Swedish railway network, individually comprising less than 0.02 per cent of the total amount of clips installed on the railway (see Table 1).

Figure 4 – Pandrol VIPA S, Pandrol VIPA F1 and Vossloh DFF (Trafikverket 2015a)

Spike clips have been used on wooden sleeper since the early stages of railways. These have later on been supplemented with base plates of steal between the rail and the wooden sleeper. The spring spike system includes a 3.5 mm rubber pad. The Hey-back clips is the strongest of the clips for wooden sleepers installed on the Swedish railway, and also includes a 3.5 mm rubber pad.

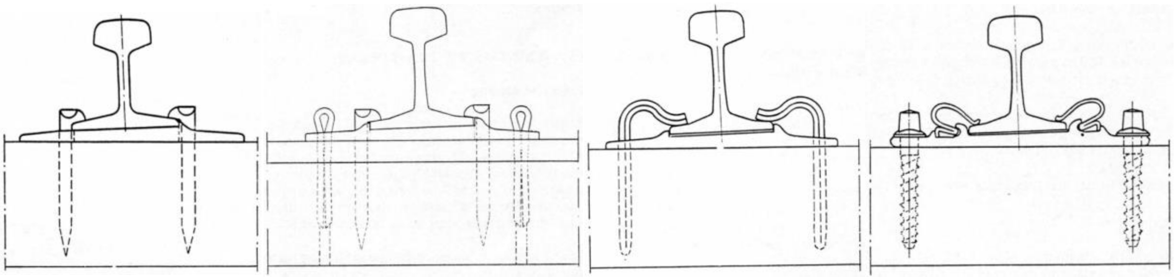


Figure 5 – Spike clip, spike with "locking nail", Spring spike system and Hey-back (Trafikverket 2015a)