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**DELIVERABLE D1.2**
Vehicle, Energy, and noise modules of UCM 2.0

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Executive Summary

This deliverable covers the scientific analysis and implementation proposal for the Vehicle, Energy, and Noise modules of UCM 2.0. UCM2.0 is the new version of the Universal Cost Model (UCM) which was made available after the H2020 Roll2Rail project. Overall, it contains a description of the upgraded UCM2.0 capabilities regarding Energy and Noise calculations and cost valuations (Task 1.3) and Vehicle damage and maintenance modelling (Task 1.4). These tasks were part of WP1-Universal Cost Model 2.0 and will have a continuation with the deliverable D1.3, entitled “UCM 2.0 tool and user guide with default parameters and recommendations”. This D1.2 deliverable together with D1.1 Infrastructure module of UCM 2.0 constitutes a full picture of the scientific background, technical developments and structure proposals for this new version of the Universal Cost Model.

The document provides an extensive study of CO₂ emissions and cost as this was an important add-in for the UCM2.0. This part analyses CO₂ emissions from rail transport, methods to monetise the cost of CO₂ emissions, how the approach is implemented in different countries and finally how these CO₂ costs are included in the Energy Module of UCM2.0. This Energy module of the UCM2.0 is based on the model of the previous UCM version, but some changes are proposed specifically some considerations regarding the relative importance of the different energy consumption terms and the energy consumption of auxiliary components. Some extensive information is provided regarding regenerative braking and energy storage systems which is valuable for the energy refeed calculations needed as inputs.

The noise module UCM2.0 is also described in detail. Starting from a background on railway noise, a full picture is given of the calculation of marginal costs of noise and valuations and regulations in transport appraisals. The noise cost calculations in UCM2.0 are based on the marginal cost of noise presented in the European Commission’s handbook on the external costs of transport [8]. The marginal costs presented are averages for EU-28, i.e., including the United Kingdom. The calculation reflects that EU member countries have different purchasing power adjusted GDP per capita.

Finally, the Vehicle Maintenance Module addresses: wear and rolling contact fatigue, condition-based maintenance and wheel reprofiling strategies. As the variety of procedures for wear and RCF calculation in the ROLL2RAIL UCM gave a variety of results due to the calibration of individual techniques a unified simplified proposal was proposed. The document evaluates it with regards to simplicity and accuracy and, as from a practical perspective, both wear and RCF are considered at the same time in the simulation, all the wear and RCF is unified in a single KPI, “reprofiling depth”, creating a much simpler interface between the simulation modules and the UCM2.0. Regarding condition-based maintenance the background and vision of an operator is included and a strategy of how to analyse CBM options in UCM2.0 is discussed.
It is important to point out that what is described in this D1.2 deliverable, and D1.1, will be complemented by the different case studies (CS) which will cover a wide range of innovations on the three different System Platform Demonstrators (metro, regional and high speed). For these analyses the new tool UCM2.0 will be used, and consequently these studies will provide an excellent knowledge base for the future users of the tool. Additionally, they will provide background on some UCM2.0 improvements that will be still possible to carry out during the project.
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<td>Cost-benefit analysis</td>
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<td>EDLC</td>
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<td>Super-conducting Magnetic Energy Storage systems</td>
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<td>System Platform Demonstrator</td>
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<td>Union Internationale Chemins de Fer. International Union of Railways</td>
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1. Introduction

Technical innovations in running gear design do not easily find their way into the market nowadays as they tend to increase the initial cost of the running gear. Still, they may reduce the system Life Cycle Cost (LCC) by lowering energy consumption and vehicle and track maintenance. The long-term cost reduction, however, is not easy to quantify. Furthermore, the initial cost must be paid by the operator of the vehicle, while the benefit due to reduced track deterioration is with the infrastructure manager. The cost for the whole railway system is also difficult to optimise.

The Universal Cost Model (UCM) is a comparison framework that accounts for all aspects of running gear innovations that influence the whole railway system's Life Cycle Costs (LCC) [1]. It is a simulation-based framework – and accompanying tools – that enable the comparison of a reference vehicle against an innovative one, showcasing the differential costs and benefits of said innovation in the railway system.

Its usage will increase the awareness of the impact of different bogie design concepts on different railway subsystems, allowing, e.g., Infrastructure Managers to assess vehicle offers for a certain system, or the influence on an existing track of a novel vehicle concept. It may even contribute to optimise maintenance and replacement cycles for Infrastructure Maintainers. Eventually, the usage of the UCM by a critical mass of stakeholders will steer the railway market to a minimisation of system-wide LCC.

1.1. THE UCM IN PRACTICE

The existing UCM was developed in the EU project Roll2Rail. The current framework and model is Excel based, modular, and in principle usable today. However, it has a number of shortcomings. Partly it is regarded as too complicated to be used, and in other parts more work on the theoretical foundation is needed. NEXTGEAR WP1 addresses both issues.

The UCM is divided in two parts (Figure 1):

1. Simulation framework for cost drivers
2. Cost calculation tool

The simulation framework defines how the simulation of the different cost drivers, or Performance Inputs, have to be calculated. In order to enable the comparison of different cases, the models for calculating these PIs should be uniform, robust, and should not leave room for interpretation. From the existing UCM, the PIs are related to vehicle and track damages, energy consumption, noise disturbances, hazards, and vehicle downtimes. The simulations target variables that are affected by improvements in running gear, and likewise, only models that can capture this impact can be used in the simulation framework.

Once the PIs have been calculated, they are used as an input for the second part, the UCM tool: an excel-based tool that implements cost concepts, maintenance procedures, etc. in order to calculate

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the cost of the different PIs. The objective is to allow the integration of all inputs in a single proxy variable: cost.

![Diagram](image)

**Figure 1. UCM framework’s conceptual representation**

### 1.2. FROM UCM TO UCM2.0

The UCM is a very valuable asset, however, the adoption of this tool by the different stakeholders has been rather limited. In some cases, the potential users have found it “complex”. Since it tackles many different aspects of the rail system, most of the users have knowledge and information with respect to a certain part of the system but lack data or information on other aspects which the tool still requires to perform an analysis. To be useful for a broad spectrum of users, the new version of the UCM needs to ensure that it suits the intended users’ needs regarding both, the calculations that can be performed and the information available for these calculations.

Additionally, there was also a need to work on the user-friendliness of the tool, on the consistency of the different modules and how they are presented, clarify which are the global inputs that affect all the modules and the ones that are module inputs. Finally, there is also a need to help the user with default values for the System Platform Demonstrators (SPD) and clarify the inputs which each module requires from the user and provide guidelines for the calculations needed to obtain these data.

Overall, the UCM2.0 required two parallel paths:

- Fill the gaps in the methodology, incorporating economic and engineering approaches
- Ensure the balance between simplicity and accuracy.

With respect to methodology, the scientific gaps in the method were explicitly listed in the call, and thus have their own descriptions in the different subsections. In order to obtain the right balance between simplicity and precision, each module has been assessed.
The UCM2.0 has aimed at bridging the gap between the UCM from Roll2Rail project and the high level KPIs developed in the S2R projects IMPACT and IMPACT-2 by reassessing the economic approach, trying to ensure that an approach from high level KPIs to UCM level KPIs is feasible. In that way, it is possible to quantify the costs of a particular “innovation” (Figure 2).

Figure 2. Illustration of the final aim of UCM2.0

UCM2.0 is a tool to help incentivising the application of innovative Running Gear Solutions through the development of an Assessment Methodology which can quantify the impacts of the running gear performance on the whole rail system economics (Figure 3).

Figure 3. Illustration of the final aim of UCM2.0
1.3. THE UCM2.0 ENERGY, NOISE, VEHICLE MAINTENANCE MODULES

This report addresses three different modules of the UCM2.0: Energy, Noise and Vehicle maintenance.

The energy consumption module from the Roll2Rail UCM is one of the modules where most effort has been expended regarding theoretical background, simulation, and cost calculation. In order to ensure that the method is valid for different implementation techniques, a benchmark simulation was performed and presented in the Transport Research Arena (TRA) 2018 Conference [2], thus providing an excellent starting point for assessing the weaknesses and gaps in the actual model. The Roll2Rail UCM model was reviewed in order to assess the relative importance of the energy calculation with respect to the overall model, including the already detected gaps such as the traction system efficiency or auxiliary bogie components, and analyse the possibilities with reducing its level of complexity without reducing its accuracy. Additionally, the Energy module of UCM2.0 tackles the CO₂ emissions and costs, and a full section is devoted in this report to this topic.

Noise from trains creates an external cost for people in the surroundings of the railway track, which has led to regulations on noise emissions in European countries. Moreover, there is also internal noise experienced by train passengers, reducing comfort and ride quality. A vehicle with better vibration isolation might for example lower the vibration level as well as increase the ride comfort. That could relax the requirement on track maintenance and in turn reduce track access charges for the vehicle (in countries where noise-related track access charges are used). There are, however, several factors determining the passengers’ subjective experience of comfort and ride quality, which make it difficult to isolate the impact of vibrations in these valuations. Still, the external costs associated with noise are included in the UCM, and the strategy has been to follow the European Commission’s handbook on external costs of transport.

The Vehicle maintenance module has tackled wheel maintenance, wear and RCF calculations. The longest possible interval for re-profiling, which is only limited by the admissible profile deviations, may not always be the most cost-efficient strategy. The reprofiling strategy can be optimised with e.g. more frequent re-profiling or tolerating certain deviations instead of fully restoring the original profile. The variety of procedures for wear and RCF calculation in the Roll2Rail UCM gave a variety of results due to the calibration of individual techniques, but a unified simplified proposal is proposed in the UCM2.0.
2. CO2 emissions and costs

Railway is one of the most energy-efficient transport modes and the mode generating significantly less CO2 (carbon dioxide) emissions compared to other transport modes [4], [5]. The modal split of railway in 2018 for EU28 was 18% of freight transport and 8% of passengers transport, although rail was only responsible for 0.5% of the CO2 emissions within the transport sector [6].

However, [7] suggest that the CO2 emissions from railways are remarkably higher if a more holistic approach is used. The main reason for the CO2 emission being underestimated in rail is because emissions from infrastructure are often neglected in life cycle impacts. Embedded emissions can arise in both the initial construction of the infrastructure and vehicles but also in the recurring maintenance and renewals. Materials used in trains and rail infrastructure such as cement, steel, aluminium, and copper give rise to significant carbon emissions. However, the carbon impact from these elements depends highly on the type of infrastructure, the type of rail (metro, long-distance or regional) and on the choice of rolling stock [7].

Running gear innovations often consider the use of new and light materials. In addition to affecting the emissions embodied in running gear, lighter materials can also reduce energy consumption, and reduce deterioration of the infrastructure (thus reducing embodied emissions). It is therefore important to consider CO2 emissions in a life cycle cost (LCC) analysis of rail transportation.

The CO2 emissions needs a price tag in order to be considered in an LCC analysis. There are two main approaches for evaluating the cost of CO2 emissions: The direct (damage cost) approach and the indirect (abatement/avoidance cost) approach. The former is based on costs related to effects of changes in sea level, water resources, human health, ecosystems etc., while the latter is based on the cost of reducing emissions according to a target set by existing policies, i.e. it is a shadow price of CO2 emissions. The environmental effects and damage caused by CO2 emissions is associated with many uncertainties and it is therefore difficult to quantify the cost of these emissions. The direct approach thus has a high level of uncertainty, generating estimates with a very wide interval, while the indirect approach has less uncertainty and reflects society’s willingness-to-pay for a certain emission level. The indirect approach is therefore used by the European Commission’s Handbook on the external costs of transport [8] (see also for example [9] and [10]). It should however be noted that there are different methods for calculating the abatement cost and they vary between countries in Europe (see sections 2.2 and 2.3).

Apart from CO2, there are other significant greenhouse gases such as methane (CH4) and nitrous oxide (N2O). These gases produce various impacts of greenhouse effects, for instance methane produces a stronger greenhouse effect than CO2. In order to compare the global warming potential of different gases, there is a general convention of converting the emissions of various gases to CO2 equivalents. In this report, however, we focus on the evaluation of the cost of CO2 emissions. Still, in the review of CO2 price tags in different countries, evaluations of CO2 equivalents are often presented, for instance in the UK.
2.1. CO₂ EMISSIONS FROM RAIL TRANSPORT

The main source of CO₂ emissions from rail transport is energy consumption. This does not, however, account for the overall emissions caused by rail transport. In addition to operations, CO₂ emissions arise when constructing and maintaining the railway system. This section will investigate the different sources of railway CO₂ emissions.

2.1.1. Energy consumption

Two energy sources are primarily used in the EU for rail transport: electric energy and energy from oil products (diesel). The use of oil products (diesel) in the railway fuel mix produces a higher CO₂ impact than electricity, although the CO₂ impact of electricity driven railway is not insignificant considering electricity produced by unsustainable sources like coal.

In the EU, the use of diesel in railways has decreased from 40.4 per cent of railway energy consumption in 2005 to 31.8 per cent in 2015, whilst the use of electricity has increased from 49.9 per cent (2005) to 67.6. (2015). The share of renewable energy has also increased, but it is worth noting that it “only” comprised 20.3 per cent of the total railway fuel consumption in 2015. [11]

Figure 1 shows the percentage of electric vs. diesel driven trains in selected EU countries based on data from Eurostat. The table shows that the number of electric trains is high in many countries although some countries rely almost entirely on diesel driven rolling stock, like Estonia and Lithuania. The table shows the number of locomotives and railcars by source of power per country, but it does not show the vehicle- or ton-km of the different types of vehicles in each country. However, this still gives some indication of the type of power used in railways in different EU countries and how the carbon footprint may vary throughout the EU.
Some EU countries are thus still highly dependent on diesel fuel for rail transport and the percentage of electrified railway lines is still low in many EU countries. In 2016, 48% of all the lines in use in the EU were electrified, where Sweden, Luxembourg, Italy, Netherlands, and Belgium are among the countries with the highest percentage of electrified railways [6]. Still, even in these countries, the emissions can vary given the different sources used for electricity production.

Figure 5 shows the production of electricity by source. Around 40% of the electricity is produced by burning fossil fuels while 35% came from renewable sources. The shares of renewables vary among EU countries, for instance, 90% of the electricity production in Cyprus and Malta come from fossil fuel while Sweden’s use of fossil fuel for energy production is minimal. [12] Hence the carbon footprint of rail can vary significantly across countries depending on use of diesel as well as on the electricity mix.

**Figure 4. Share of trains (locomotives and railcars) by source of power per country in 2018. Germany data from 2015 and only for locomotives. Italy and Greece data from 2017. Data source: Eurostat [6], own calculations.**
There are indeed different emission levels from electricity depending on which country it is produced in. This is shown in Figure 6 where the number of gram CO₂ equivalents per kWh is presented per country during 2018 and 2019. The data is provided by the European Environment Agency (EEA) and based on emissions from all electricity generation and total electricity production (see [13] for more details on the methodology).

Figure 5. EU production of electricity by source. Illustration from Eurostat [12]
2.1.2. Infrastructure and rolling stock

As previously mentioned, the railway carbon footprint is smaller compared to that of other transportation modes such as road and aviation. However, apart from energy consumption, which is the largest contributor to the carbon footprint, \( \text{CO}_2 \) emission arise in all phases of a transport mode’s life cycle. \( \text{CO}_2 \) emissions arise in the materials and energy used in infrastructure construction and then in the infrastructure renewal and maintenance. Moreover, embedded emissions arise from different components and materials used in the production and maintenance of the rolling stock [7], [14].

Evaluating the total carbon footprint of rail transport can be more difficult comparing to other transport modes due to the nature of the railway system. This is because rail infrastructure needs many supporting components such as stations, tunnels, overhead line equipment (OLE), signalling and telecommunications, and vehicles, where each component produces various carbon effects. This relatively complex system may imply larger effects on emissions when compared to other transportation modes, for instance road. It is shown that infrastructure construction and maintenance may comprise possibly up to 20 % of the total rail carbon footprint [7]. Although many studies evaluate the \( \text{CO}_2 \) effect of rail in different life cycle phases (see e.g., [15]; [16]; [17]), the estimates vary greatly due to (1) the different types of infrastructure in different countries (complexity of the structure) and (2) the different types of railway in a given country such as metro, tramway, regular long-distance or high-speed rail [7].
A report commissioned by UIC [18] provides calculations for the overall carbon footprint from a life cycle perspective of passenger/freight rail transport in selected countries. A summary of the information from this study is provided in Figure 7 and Figure 8. The carbon footprint for road traffic (cars and lorries) is given for comparison. These figures show that the emissions from the rolling stock and the track system (infrastructure) are not negligible and constitute a significant part of the overall rail carbon footprint. However, the carbon effect from rail operations (fuel) is the most important, comprising the largest carbon impact. The figures also show that the infrastructure carbon impact is country specific, that is, it depends highly on kind of rolling stock used, electrification system as well as differences in climate and geography.

![Figure 7. Overall carbon footprint for passenger rail transport in selected countries. Source: [18]](image1)

![Figure 8. Overall carbon footprint for freight rail transport in selected countries. Source: [18]](image2)
2.2. Methods to monetise the cost of CO₂ emissions

CO₂ emissions are negative externalities that need to be accounted for in a LCC analysis of rail transportation. The two most well-established methods to monetise the cost of CO₂ emissions are the direct (damage cost) approach and the indirect (abatement/avoidance cost) approach. The direct approach is based on the cost of the actual damage CO₂ emission give rise to, such as costs associated with adverse human health, changes in the sea level, water resources, ecosystems etc. The indirect approach is based on the cost of reducing emissions through existing policies such as taxes or the EU Emission Trading System (ETS). The following sections will further describe the different methods to monetise CO₂ emissions and review which emissions are already internalised in the so-called traded sector within the EU ETS.

2.2.1. Direct approach

The damage caused by climate change includes effects such as rising water levels, water shortage, and declining crop yields [19]. The direct approach considers the marginal social cost of the different damages caused by carbon emission, that is, the cost of one additional unit of CO₂ to society. However, this approach has certain drawbacks. The long-term damages from CO₂ emissions are uncertain and very difficult (if not even impossible) to estimate. It is therefore difficult to determine the damage cost that CO₂ causes. Another complicating factor for determining damage costs is that it is not the flow but the concentration of CO₂ that affects the climate, and it also remains in the atmosphere for long periods which complicates the marginal cost of CO₂ further. [20], [9]

Despite the difficulties of using the direct approach, there is an extensive literature on this approach. However, these were mostly conducted during the 1990’s and in the beginning of 2000 in the US (e.g., [21], [22]), and the calculated marginal costs of CO₂ varies significantly. The variation in the estimates is due to the uncertainty in the underlying damage estimates, and uncertainty about future emissions and future climate change [23]. The most well-known valuations of CO₂ emissions were conducted by [19], which however does not account for the possibilities of catastrophes since the uncertainties associated are (were) high.

2.2.2. Indirect approach

The indirect (abatement/avoidance cost) approach considers the cost of reducing CO₂ and can be based on the so-called shadow price of carbon (SPC) or tradable permit schemes such as the EU ETS [24]. The SPC reflects the costs to achieve the goals set by climate policies. This could be costs related to existing policies such as a tax rate on carbon emissions, or the tax rate that would be required to reach a specific reduction target for CO₂ emissions [20]. Although, using the existing tax rate to determine a CO₂ cost has limitations since it may partly be fiscal (i.e., the purpose is to gain revenue), and there are often other measures aimed at reducing CO₂ emissions that also needs to be taken into account to reflect the SPC [20].

A tradable permit scheme such as the EU ETS is a policy that sets a limit on the total amount of greenhouse gas emissions. Over time, the number of tradable permits is reduced so that the total
emission reduces. The European Commission distributes a limited number of permits or emission allowances to companies. Companies that want to increase their emissions must purchase permits from others that are willing to sell theirs [26]. The price of these permits can thus be used to quantify the cost of CO₂ emissions. However, when conducting a monetary valuation, it is important to distinguish between emissions that are included (traded sector) and those that are not (non-traded sector): see further in section 2.2.3. The cost of the emissions included in the traded sector are considered to be internalised given the requirement for relevant sectors to buy permits to cover additional emissions [27]. Although, like the carbon tax, a drawback with this indirect approach is the reliance on targets set by decision-makers.

Overall, the method relies heavily on political decisions to put a price tag on CO₂ emissions, yet, to make such decisions, information regarding the damage cost of CO₂ is required [9], [25], and both the direct and indirect approach are thus necessary [24].

In summary, the indirect approach such as shadow pricing or traded permit schemes are based on the cost of reducing emissions set by existing policy. The method is however highly dependent on political decisions, which may not reflect the actual damage that the emissions cause.

2.2.3. The traded sector

When determining the cost of CO₂ emissions within a certain industry, it is important to consider the parts already compensated for, i.e., the CO₂ costs that are already internalised. As discussed in sections 2.2.1 and 2.2.2, the emissions stemming from rail have several sources. The main source is the energy consumption, both coming from diesel but also from electricity as electricity can be produced by emission-intensive power plants. Other emission sources are the production of materials used in the infrastructure and rolling stock such as cement and steel.

The sectors included in the EU ETS are power and heat generation and energy-intensive industries such as oil refineries, steel works and production of iron, aluminium, metals, cement, and other materials. Commercial aviation is also included as of 2013. Electricity production is included in the trading system (power and heat generation industry) which means that the CO₂ emissions from electricity-driven trains are at least partly internalised. Thus, whether a country has a CO₂-intensive production of electricity becomes less relevant because the producers (at least to some extent) pay for their carbon footprint.

Likewise, the production of steel, cement and aluminium is in the traded sector which means that embedded emissions from these materials are covered by EU ETS. However, if these materials are imported from outside the EU, they are most likely not internalised. For instance, the net trade balance for steel was negative in 2019 in the EU. The top three EU import sources for steel are Turkey, Russia and Ukraine which have softer or no constraints on greenhouse gas emissions [28]. How much of these imported materials are used in railway infrastructure and rolling stock is not yet conclusive.
An important aspect that needs to be accounted for when assuming internalised CO₂ costs is whether the price offsets the actual cost. The price of carbon has varied greatly since the trading system was introduced in 2005: from zero € per tonne CO₂ to around € 60 per tonne CO₂ (October 7, 2021). Since the ETS carbon price is a market price, it is a good basis for CO₂ cost evaluation. However, this applies only if the market functions properly – that is, if the price is determined by the supply and demand for emission rights. This is not the case for EU ETS as the supply of emission rights – the emission cap – is politically determined and adjusted every year to a level that is not necessarily socio-economically efficient. [20] In addition, the EU ETS price will be efficient when carbon emissions from all sectors are included, which means that this price is not representative for emissions in the non-traded sector [8]. Overall, if the carbon price is not optimally set, the cost of CO₂ is not fully internalised by the ETS, which needs to be considered when determining the cost of CO₂ emissions from rail transport.

The greenhouse gas emissions that are not in the EU ETS are in the non-traded sector, the so-called Effort Sharing Regulation (ESR). The EU sets certain emission reduction goals for the non-traded sector which are implemented in various ways in each member state, for example through CO₂ taxes on petrol, diesel, or coal. The ESR proposes cutting emissions from the non-ETS sector to at least 75% by 2040, compared to emissions in 1990. For the transport sector, emissions from domestic transport ought to be cut by 70% by 2030, excluding domestic aviation which is included in the ETS. [32]

### 2.3. CO₂ EVALUATIONS IN DIFFERENT COUNTRIES

#### 2.3.1. Germany

The German transport appraisal guideline is using the damage cost approach to derive the cost of CO₂ emissions [29]. The recommended value is € 180 per tonne CO₂ and is based on calculations from the FUND damage cost model [30]. This value is close to the recommended value in the 5th Assessment Report of the IPCC which is around $ 209 per tonne CO₂ ([23], p. 691).

Differentiated evaluations for greenhouse gases from fuel combustion, abrasion, and suspension are provided in [29]. The cost rates are per vehicle kilometre for various vehicle types and transport modes. Table 1 presents the values for rail vehicles. The cost rates differentiate between passenger long distance (electric) trains, passenger local (electric and diesel) trains, and freight (electric and diesel) trains. Emissions from electric trains are set to zero due to electricity production being under the EU ETS cap, while the cost for diesel trains are high. For cost rates per passenger or tonne kilometre, the average utilisation rates per type of train are required and these are given in the report and can therefore be easily calculated.

In addition to costs for train operations, [29] provide costs for emissions from other life cycle phases, such as emission costs arising in construction of the infrastructure and vehicles. These costs are
based on [31] and considers processes such as material, energy and water use in vehicle manufacturing. The pre-process emission costs are quite large comparing to other transportation modes. However, if these costs are divided by train-km or passenger-km, the costs become comparatively low.

Table 1. Environmental costs per vehicle kilometre for different vehicle types in Germany in €-Cent2016 per vehicle km

<table>
<thead>
<tr>
<th>Vehicle category</th>
<th>Operation</th>
<th>Emission concept</th>
<th>Pre-processes</th>
<th>Energy supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger train, long-distance</td>
<td>Electric</td>
<td>201.50</td>
<td>219.01</td>
<td></td>
</tr>
<tr>
<td>Passenger train, local train</td>
<td>Electric/Diesel</td>
<td>59.13</td>
<td>89.36</td>
<td></td>
</tr>
<tr>
<td>Freight train</td>
<td>Electric/Diesel</td>
<td>276.72</td>
<td>198.74</td>
<td></td>
</tr>
</tbody>
</table>

Source: [29]. The value for passenger local trains and freight trains is a weighted average for diesel- and electricity driven trains.

2.3.2. Sweden

In Sweden, the cost of carbon is evaluated using the indirect approach. The value is based on the carbon dioxide tax that would be necessary in order to achieve the domestic climate goals, for instance the goal to achieve fossil-free road traffic and a 70% reduction in emissions by 2030 within the transport sector [32]. Since new climate goals have been proposed over the years, especially in the transport sector, the price of CO$_2$ has been drastically increased in 2020, from around 2 SEK per kg CO$_2$ to 7 SEK per kg CO$_2$. For rail transport, the average marginal cost of carbon dioxide emissions for railcars and locomotives are set at SEK 17.78 per litre diesel (2017 prices).

The emission factors for carbon dioxide indicate emissions from diesel without admixture of renewable fuel. The emission factor refers to the actual emissions due to traffic and not emissions from a life cycle perspective [32]. Since the unit is in SEK per litre of diesel, the marginal cost does not capture variations in fuel consumption between different vehicles and different traffic situations, for instance long distance or regional rail transport. It can be noted that carbon emissions have a global environmental effect regardless of where the emissions occur and when, and the marginal cost of carbon dioxide emissions per litre of diesel is therefore the same regardless of the type of traffic environment and year. The marginal cost of carbon for electric rail transport are considered to be zero. [32]

2.3.3. Netherlands

The cost of carbon in the Netherlands is provided by the General Guidance for cost-benefit analyses [33]. The values proposed are to be used in Cost Benefit Analyses (CBAs) of any kind of project (including transport) and are given as efficient prices and as ETS prices in three different climate scenarios (see Table 2). Scenario “High” corresponds to a scenario where larger emissions reduction can be achieved, scenario “Low” corresponds to lower CO$_2$ reductions and scenario “2°C” where the world manages to stay under the global temperature increase of two degrees Celsius [34]. Both
EU ETS prices and the so-called “efficient” prices are presented in the Table 2 for years 2015, 2030 and 2050. The efficient price is an alternative to the market price (the ETS price) since the latter can be disturbed by market failure (see section 2.2.3). In this case, the efficient price is said to be a welfare efficient price of carbon. Since the prices proposed are to be used in any type of CBA, there are no differentiated carbon prices for rail.

Table 2. Efficient prices and EU ETS prices used in the Netherlands. € per tonne CO₂ in 2015, 2030 and 2050.

<table>
<thead>
<tr>
<th>Climate scenario</th>
<th>Type of price</th>
<th>2015</th>
<th>2030</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Efficient price</td>
<td>48</td>
<td>80</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>ETS price</td>
<td>5</td>
<td>40</td>
<td>160</td>
</tr>
<tr>
<td>Low</td>
<td>Efficient price</td>
<td>12</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>ETS price</td>
<td>5</td>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td>2°C</td>
<td>Efficient price</td>
<td>60–300</td>
<td>100–500</td>
<td>200–1000</td>
</tr>
<tr>
<td></td>
<td>ETS price</td>
<td>5</td>
<td>100–500</td>
<td>200–1000</td>
</tr>
</tbody>
</table>

Source: [33]

2.3.4. France

The carbon price in the French guideline on socioeconomic evaluation of public investments is based on a review of studies that evaluate the social cost of carbon with different methodological approaches [35]. The value proposed by Boiteux II (€ 32 per tonne CO₂) is then used as an initial value that grows with a rate of 5.8 per cent over the period 2010-2030. The price is generalised for all types of projects. Differentiated carbon values per transport mode are not proposed in the guideline.

2.3.5. Denmark

The Danish transport guideline bases their CO₂ price on the current price in the EU ETS’s quota system [36]. The stated reason for this is that the ETS trading system reflects the willingness to pay for emissions and are thus well-suited to be used in the transport sector as well, even though the transport sector is not included in the ETS (except for aviation, see section 2.2.3). The Danish value of CO₂ emissions is thus not based on the damage costs of the emissions, but on the trade value of CO₂ in the EU ETS.

The unit price is per tonne CO₂ and is not differentiated between different types of modes. Still, a distinction is made between the average emission level (measured in grams CO₂) per transport mode: cars (diesel, petrol or electric), truck (diesel), bus (diesel), passenger train (diesel or electricity), freight train (diesel or electricity). Regarding CO₂ emissions from electricity-driven vehicles, the recommendation is not to include the CO₂-cost in the calculation because electricity production is covered by the EU ETS quota system.
2.3.6. United Kingdom

The carbon price in the Transport Analysis Guidance of the Department for Transport of the United Kingdom (TAG) is based on the avoidance cost (indirect) approach. This involves estimating the expenditure that is necessary to achieve a CO\textsubscript{2} reduction target. The average price or the average abatement cost per emitted tonne CO\textsubscript{2} is then calculated. Table 3 presents the values proposed in TAG for the non-traded sector where rail is included. Three scenarios are presented: “High”, “Central”, and “Low” and for the period 2010-2100. The carbon prices presented in the table are for the period 2019-2025.

Table 3. Non-traded values of CO\textsubscript{2} in the UK TAG, £ per tonne CO\textsubscript{2} equivalents (2010 prices).

<table>
<thead>
<tr>
<th>Year</th>
<th>Low</th>
<th>Central</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>29.55</td>
<td>59.09</td>
<td>88.64</td>
</tr>
<tr>
<td>2020</td>
<td>30.42</td>
<td>59.96</td>
<td>90.38</td>
</tr>
<tr>
<td>2021</td>
<td>30.42</td>
<td>60.83</td>
<td>92.12</td>
</tr>
<tr>
<td>2022</td>
<td>31.29</td>
<td>62.57</td>
<td>92.99</td>
</tr>
<tr>
<td>2023</td>
<td>31.29</td>
<td>63.44</td>
<td>94.72</td>
</tr>
<tr>
<td>2024</td>
<td>32.15</td>
<td>64.31</td>
<td>96.46</td>
</tr>
<tr>
<td>2025</td>
<td>33.02</td>
<td>65.18</td>
<td>98.20</td>
</tr>
</tbody>
</table>

Source: Transport Analysis Guidance, TAG UNIT A3 Environmental Impact Appraisal [27].

2.3.7. EU – Handbook on external costs of transport

The European Commission have developed a handbook on the external cost of transport, which includes the marginal cost of CO\textsubscript{2} caused by rail in Europe. The indirect approach (abatement cost) is used to quantify the cost of climate change, which in this case corresponds to efforts required to stabilise global warming at 2°C – the goal supported by the United Nations Framework Convention on Climate Change (UNFCC) [10]. In the most recent handbook [8], three input values are used to quantify the cost of climate change caused by greenhouse gases (GHG); the GHG emission factors per vehicle type, vehicle performance data and climate change costs per tonne of CO\textsubscript{2}. The handbook also includes the climate cost of other GHGs (e.g. CH\textsubscript{4} (methane) and N\textsubscript{2}O), which are transformed into CO\textsubscript{2}-equivalents.

Table 4 provides the marginal cost of the climate change caused by railway differentiated by passenger trains and freight trains run by diesel from the most recent EU handbook. The marginal cost of the greenhouse gases is expressed in €-cent per train-km for both passenger and freight trains. In addition, the marginal cost for passenger trains is expressed in €-cent per passenger-km (pkm) and in ton kilometres (tkm) for freight trains. It is clear that freight trains entail higher emissions per train-km compared to passenger trains.
Table 4. Marginal external climate costs (2016) of rail transport, EU-28

<table>
<thead>
<tr>
<th>Train type</th>
<th>Traction</th>
<th>Unit cost</th>
<th>Load factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>€-cent/passenger-km</td>
<td>€-cent/train-km</td>
</tr>
<tr>
<td>Passenger transport</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercity train</td>
<td>Diesel</td>
<td>0.201</td>
<td>17.5</td>
</tr>
<tr>
<td>Regional train</td>
<td>Diesel</td>
<td>0.735</td>
<td>22.8</td>
</tr>
<tr>
<td>Freight transport</td>
<td></td>
<td>€-cent/ton-km</td>
<td></td>
</tr>
<tr>
<td>Long container</td>
<td>Diesel</td>
<td>0.158</td>
<td>118.2</td>
</tr>
<tr>
<td>Long bulk</td>
<td>Diesel</td>
<td>0.087</td>
<td>122.5</td>
</tr>
<tr>
<td>Short container</td>
<td>Diesel</td>
<td>0.074</td>
<td>103.2</td>
</tr>
<tr>
<td>Short bulk</td>
<td>Diesel</td>
<td>0.066</td>
<td>105.9</td>
</tr>
</tbody>
</table>

Source: [8]

Electric trains are not included in Table 4 since the marginal costs of climate change are zero for the direct (“tank-to-wheels”) emissions from these trains. However, electric trains generate emission costs through the energy production, as discussed in section 2.1.1. These are referred to as the cost of well-to-tank emissions which equates the energy productions including the production of all different types of energy sources leading to for example GHGs. The EU handbook therefore include the marginal cost of well to tank emissions for electric trains, differentiated by passenger trains and freight trains, where 60–65% percent of these costs are GHG costs, and the rest is air pollution costs [8]. The marginal external well-to-tank costs for rail transport are presented in Table 5. Recall that electricity production is included in the EU ETS, i.e., the traded sector (see section 2.2.3), and at least a part of the well-to-tank emissions are thus internalised.

Table 5. Marginal external well-to-tank costs (2016), EU-28

<table>
<thead>
<tr>
<th>Train type</th>
<th>Traction</th>
<th>Unit cost</th>
<th>Load factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>€-cent/passenger-km</td>
<td>€-cent/train-km</td>
</tr>
<tr>
<td>Passenger transport</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High speed train</td>
<td>Electricity</td>
<td>0.39</td>
<td>117.4</td>
</tr>
<tr>
<td>Intercity train</td>
<td>Electricity</td>
<td>0.73</td>
<td>117.4</td>
</tr>
<tr>
<td>Intercity train</td>
<td>Diesel</td>
<td>0.18</td>
<td>16.1</td>
</tr>
<tr>
<td>Regional train</td>
<td>Electricity</td>
<td>0.89</td>
<td>97.9</td>
</tr>
<tr>
<td>Regional train</td>
<td>Diesel</td>
<td>0.26</td>
<td>8.0</td>
</tr>
<tr>
<td>Freight transport</td>
<td></td>
<td>€-cent/ton-km</td>
<td></td>
</tr>
<tr>
<td>Long container</td>
<td>Electricity</td>
<td>0.11</td>
<td>151.3</td>
</tr>
<tr>
<td>Long bulk</td>
<td>Electricity</td>
<td>0.10</td>
<td>156.8</td>
</tr>
<tr>
<td>Short container</td>
<td>Electricity</td>
<td>0.26</td>
<td>132.0</td>
</tr>
<tr>
<td>Short bulk</td>
<td>Electricity</td>
<td>0.18</td>
<td>135.4</td>
</tr>
<tr>
<td>Description</td>
<td>Fuel</td>
<td>CO₂</td>
<td>Price</td>
</tr>
<tr>
<td>--------------------</td>
<td>--------</td>
<td>------</td>
<td>-------</td>
</tr>
<tr>
<td>Long container</td>
<td>Diesel</td>
<td>0.03</td>
<td>42.0</td>
</tr>
<tr>
<td>Long bulk</td>
<td>Diesel</td>
<td>0.03</td>
<td>43.5</td>
</tr>
<tr>
<td>Short container</td>
<td>Diesel</td>
<td>0.07</td>
<td>36.7</td>
</tr>
<tr>
<td>Short bulk</td>
<td>Diesel</td>
<td>0.05</td>
<td>37.6</td>
</tr>
</tbody>
</table>

Source: [8]

Another aspect that is not covered by the marginal cost in Table 5 is the emissions caused by the rail infrastructure. The GHG emissions caused by the production of the rail infrastructure is important from a life cycle perspective on the emissions. Similar to vehicles, the construction, maintenance, and disposal of assets leads to emissions [10]. Even though this aspect is mentioned and discussed, the handbook does not include a specific cost for the emission of the infrastructure of rail.

### 2.3.8. Discussion of appraisals

Currently, there is no standardised approach used to monetise the cost of CO₂. This is illustrated by the diversity of methods and costs of CO₂ in appraisals across countries.

The Swedish, UK and Danish appraisals use the indirect approach to monetise CO₂ emissions, which are based on the cost of reducing CO₂ emissions according to a target set by existing policies. For example, the Swedish appraisal depends heavily on the Swedish carbon tax [32], whilst the UK appraisal rely on the estimated abatement costs per tonne of carbon dioxide to achieve the government emission target [27]. The Danish appraisal on the other hand bases the valuation on the price of tradable permits of carbon, despite the fact that the transport sector is not (fully) included in the trading system of permits. Hence, the Danish appraisals use the price of the permits and the changes of the price of permits over time as a proxy of the value of CO₂-emissions within the transport sector [36]. The German appraisal present different values, some of which are based on the indirect approach and others that are based on the direct method (damage cost) [29]. The indirect approach – which many of the appraisals base their valuation on – relies heavily on political decisions such as targets set by decision-makers, and thus the value does not necessarily reflect the actual cost that the CO₂-emission give rise to.

The UK appraisal emphasise the importance for appraisals to include all GHGs including those arising from the investment of infrastructure, for example cement, steel etc., known as embedded carbon. Although most of such embedded carbons are likely to be covered by EU ETS and the cost of these emissions are therefore internalised [27].

Furthermore, targets and measures to reduce emissions can vary over time depending on the political arena at the specific time, which in turn affect the valuation of CO₂-emissions. For instance, the Swedish appraisal has increased the value of CO₂ dramatically in their most recent appraisal, mainly due to political targets and measures which increases due to more ambitious environmental targets. However, it is not the only reason the value of CO₂ increases over time. The Swedish appraisal
guideline states that an annual growth rate based on the development of GDP/capita should be accounted for in the external cost of CO$_2$-emissions [32].

Most of the appraisals include different values for different time periods. For example, the UK appraisal guideline presents a cost for each year from 2010 until 2100, whilst the Dutch guideline makes a distinction between short-term (2010), medium-term (2030) and long-term (2050). By contrast the Swedish appraisal guideline does not provide different values depending on time.

It is evident that there is no standardised method to calculate the external effects of CO$_2$-emissions since the appraisals across the EU vary greatly.

2.4. **Example calculations of CO$_2$ emissions and costs in rail transport**

2.4.1. **CO$_2$ emissions from rail infrastructure**

CO$_2$ emissions of rail infrastructure from a life cycle perspective can be calculated with the tool Klimatkalkyl [37] version 7.0, maintained by the Swedish Transport Administration. The tool is developed to enable comparable estimates of the climate effect and energy consumption from transport infrastructure. The tool is based on the life cycle analysis (LCA) methodology and takes into account the production and transport of construction materials, maintenance, and emissions from machinery. End-of-life of the total infrastructure component is not included per default because railways are seldom decommissioned. The decommissioning of materials as part of maintenance work is assumed to be negligible compared to the production of the new materials.

The example calculations are based on the track superstructure, consisting of the rail, fasteners, sleepers, and ballast. Included in maintenance for the permanent way is heating of switches, electricity for point machines and rail grinding. Other types of maintenance that also occur was not deemed to have a large effect, e.g., snow removal and inspections.

The Klimatkalkyl tool is based on Swedish conditions, to a large degree from a study [38] of the Bothnia Line. Emission factors for the included materials and transports are based on different literature reviews and Environmental Product Declarations (EPDs) and are presented in [39]. Standard values for goods transportation distances to the site are used but can be altered if the transport distances are known.

For rail infrastructure with a lifetime of 50 years, the calculated CO$_2$ emission is 9.7 tonnes of CO$_2$e per km and year, of which the rail is the largest emission source and contributes to 66% of the total emissions. The second largest emissions arise from the sleepers, which contribute to 19% of the total emissions. Because of the high emissions from the rail production, this value is also very sensitive to changes in the rail weight. On stretches with less traffic, rails with a weight of 50 kg/m can be used instead of 60 kg/m, which gives reductions of 1.1 tonnes of CO$_2$ per km and year or 11
per cent of the total emissions. The lifespan of the rail also has a large impact. For example, prolonging the lifespan by 10 years, the emissions decrease by approximately the same amount as reducing the weight by 10 kg/m.

All the electricity used for maintenance, transport etc. is assumed to be renewable energy, because the Swedish Transport Administration only buys renewable energy for the management of their railways and roads. In cases where non-renewable energy is used the transport emissions can therefore be significantly higher, e.g. by substituting the train emission factor from the current 12 g CO₂e/kWh to 285 g CO₂/kWh, the average electricity emission factor for EU, the total emissions increase by 12.5 tonnes CO₂/year or 128 per cent.

2.4.2. CO₂ emissions from trains

Train life-cycle data has been obtained from public EPDs, where total emissions from trains are presented, yet without information on the different components of the train. These are all from modern trains produced during the 00s or 10s. The trains are commuter, regional or long-distance trains with maximum speeds of 72 to 200 km/h manufactured by Bombardier, Bombardier-Alstom, Alstom, and CAF. The emissions from production and assembly are representative for the location of production. Emissions during operation is based on an electricity mix or diesel emission factor relevant for where the train is run, which gives widely varying results. Therefore, the GHG emission intensity for electricity for all EU countries can be considered (see Figure 3), so that the emissions from train operation can be calculated for a selected country.

The reported emissions from the train’s life cycle are in the range 1 to 39 g CO₂e/passenger-km in the selected the EPDs. The trains are, however, modelled with different passenger loads. This is realistic because some routes are more heavily trafficked than others. Multiplying the emissions with the number of passengers used in the estimates, this results in emissions in the range 305 to 6152 g CO₂/km. When excluding the train operation from the calculation, the emissions are in the range 134 to 195 g CO₂/km.

One of the trains, the Coradia Polyvalent, can also be run on diesel, which gives significantly higher emissions from the operation compared to using electricity according to their calculations. However, the emissions from the diesel mode are in the same order of magnitude as when running the train on electricity from some of the countries with larger share of non-renewable electricity sources.
3. UCM2.0 Energy Module

The activities described in this section correspond to Task 1.3:

3.1. THE ENERGY MODULE IN UCM

3.1.1. The calculations required as inputs for the module

The Energy module in UCM requires the user to calculate the total Energy consumption due to resistances when running from A to B. In order to do so, the following terms were proposed:

- Rolling resistance
- Curve resistance
- Unstable running resistance
- Starting resistance
- Gradient resistance
- Aerodynamic resistance
- Turbulence resistance
- Tunnel resistance
- Dynamic resistance/inertia resistance
- Auxiliary components

Therefore, the total energy consumption was calculated using this equation:

\[
E_T = E_{RR} + E_{CR} + E_{UR} + E_{SR} + E_{AR} + E_{GR} + E_{TU} + E_{IR} + E_{Aux} - E_{rec/feed} \text{ (kWh)}
\]

where

- \(E_{RR}\) = Energy consumption due to rolling resistance (kWh)
- \(E_{CR}\) = Energy consumption due to curve resistance (kWh)
- \(E_{UR}\) = Energy consumption due to unstable running (kWh)
- \(E_{SR}\) = Energy consumption due to starting resistance (kWh)
- \(E_{AR}\) = Energy consumption due to aerodynamic resistance (kWh)
- \(E_{GR}\) = Energy consumption due to gradient resistance (kWh)
- \(E_{CR}\) = Energy consumption due to turbulence resistance (kWh)
- \(E_{TB}\) = Energy consumption due to inertia resistance (kWh)
- \(E_{TB}\) = Energy consumption due to tunnel resistance (kWh)
- \(E_{Aux}\) = Energy consumption due to auxiliary components (kWh).
- \(E_{rec/feed}\) = Energy recovered/reefeed (kWh).

The calculation methodology for each term in the previous equation is described thoroughly in the Roll2Rail deliverables “D4.3 Cost model /Methodology”, and its annexes [1]. Specifically, for the energy module the “Annex B: Calculation of energy consumption and refeed” and the deliverable UCMf1.5 “Procedure for calculating cost of energy” [3].
It is important to point out that the calculations of the different terms of the total energy consumption were not carried out within the UCM tool. The excel tool required the user to perform these calculations – for which the documentation was giving some guidelines – and provide the calculation results as an input to the energy module.

### 3.1.2. Considerations of the relative importance of the different energy terms

An interesting assessment of the UCM, and specifically of the energy module, was carried out by some partners of the Roll2Rail project and presented in the TRA 2018 conference [2]. The groups involved in the benchmark were KTH Royal Institute of Technology, CAF I+D, Siemens (SIE), Stadler Rail Valencia (STDV), and VIRTUAL VEHICLE Research Centre (ViF).

In order to ensure that all the calculation tools developed by the different partners were adequate, a benchmark simulation was carried out. The benchmark studies a high-speed vehicle composed of two powered units and four non-powered ones, including six conventional bogies and three Jacobs bogies with both mechanical and ED brakes. To validate the simulation, the share of energy consumed is then compared in different concepts, including in the fields of rolling resistance, curve resistance, unstable running resistance, gradient resistance, aerodynamic and turbulent resistance, inertia resistance, and energy use of auxiliary elements. It should be stressed that the comparison and validation focus on bogie-influenced energy consumption, this being:

- Rolling resistance, which accounts for the wheel-rail contact resistance and bearing resistance.
- Unstable running resistance, which accounts for the internally dissipated energy in e.g. dampers.
- Aerodynamic resistance, which accounts for the viscosity of the surrounding air.
- Turbulence resistance, which accounts for the extremely turbulent aerodynamic behaviour close to the running gear.
- Gradient resistance, which accounts for the uphill and downhill gradients.
- Curve resistance, which accounts for the energy dissipation in the wheel rail contact because of imperfect steering.
- Inertia resistance, which accounts for the accelerated and decelerated masses in the vehicle.

In order to study all the aspects within the energy calculation procedure, a reference track and a reference vehicle were defined. Full details can be found in the TRA 2018 paper [2], but the following tables show a synthesis of the results obtained by the different partners.
Some conclusions were extracted from this benchmark (note that the reference case was a high-speed vehicle):

- Starting resistance and Tunnel resistance are not affected by changes in running gear design and could therefore be omitted.
- Turbulent Resistance is negligible.
- Curve Resistance is negligible. This conclusion should be taken carefully, as it could have a higher relative importance for low speed and curvy routes or different type of vehicles (metro vehicles or regional trains).
- Rolling Resistance and Unstable Running Resistance have a relatively low importance.
- Aerodynamic Resistance is important, but there are substantial variations between the partners.
- Gradient Resistance is not captured correctly.

### 3.1.3. Conclusions for the UCM2.0 energy module

There are several conclusions which can be extracted from the previous subsection and additional discussions among NextGear-WP1 partners for the implementation of the UCM2.0. When
performing the energy calculations, the user has to bear in mind that the UCM2.0 aims at quantifying the potential benefit of innovations and therefore the emphasis is on the comparison between the reference vehicle and the vehicle which includes the technological innovation. This means that when carrying out the calculations in the different modules, the inputs to the different modules are important but the focus should be on the “relative changes” that the innovation implies. As an example, if a vehicle with a new steering system is to be analysed the calculation of the aerodynamic resistance could be simplified.

For the UCM2.0 module the following conclusions were adopted:

- Starting resistance and Tunnel resistance are not affected by changes in running gear design, and therefore the general recommendation is that the user can omit them when calculating the total energy consumption.
- Turbulent Resistance is negligible, and therefore the general recommendation is that the user can omit them when calculating the total energy consumption.
- Unstable Running Resistance has a relatively low importance, and therefore the general recommendation is that the user can omit it when calculating the total energy consumption.
- Curve Resistance importance depends on the type of vehicle and route. Further discussions can be found in the module inputs guidelines for the UCM2.0.
- Aerodynamic Resistance is important, and should be included for speeds over 200 km/h.
- Regarding the gradient resistance, UCM2.0 requires the user to calculate a round trip (A to B and back to A) instead of just from A to B as in the previous version.

3.2. THE ENERGY MODULE IN UCM2.0

3.2.1. The Energy cost in UCM2.0

The energy module in UCM2.0 calculates the total energy costs (how the CO₂ emission cost is included is explained in 3.2.4 of a round trip (A-B-A) from the previously calculated energy consumption.

The total energy consumption running from A to B and back to A (ABA) is an input from the user and has to include the rolling, gradient, aerodynamic and curve resistance, and – if considered relevant – other energy consumption terms such as: auxiliary components, tunnel resistance, unstable running, etc..

\[ E_{TOTAL} = E_{RR} + E_{GR} + E_{IR} + E_{AR} + E_{CR} + E_{OTHER} \] (kWh)

where

- \( E_{RR} \) = Energy consumption due to rolling resistance (kWh)
- \( E_{GR} \) = Energy consumption due to gradient resistance (kWh)
- $E_{IR} = \text{Energy consumption due to inertia resistance (kWh)}$
- $E_{AR} = \text{Energy consumption due to aerodynamic resistance (kWh)}$
- $E_{CR} = \text{Energy consumption due to curve resistance (kWh)}$
- $E_{OTHER} = \text{Energy consumption due to auxiliaries, unstable running, tunnel, etc.. (kWh)}$

Additionally, the module requires the Energy refeed running from A to B and back to A (kWh), $E_{\text{rec/feed}}$ (Energy recovered/refeed (kWh))

The methods to calculate the different terms were specified in Roll2Rail D4.3 report: D4.3 Universal cost model development [1].

The user may have measured data on the consumption running the round-trip A-B-A from similar vehicles. In this case, the experimental value can replace the energy consumption calculations.

### 3.2.2. Energy consumption due to auxiliary components in UCM2.0

The energy consumption of auxiliary components has been included in the term $E_{OTHER}$ because in most cases it does not have a significant influence in the total energy consumed by the vehicle. It is the same case as the energy consumed due to unstable running, tunnel, starting, and turbulence resistances. The reason to do so is to highlight the other important factors in energy consumption and avoid the user to carry out extra calculations for the model inputs which in the end will not affect the final result.

Although the following list of terms (which are not included in the different driving resistances) is not exhaustive, it provides an indication of auxiliary components organised from more to less likely to be influential in the total energy consumption:

1. Active steering/primary suspension systems ($E_{\text{AST}}$)
2. Active high bandwidth secondary suspension systems ($E_{\text{HBAS}}$)
3. Active low bandwidth secondary suspension systems ($E_{\text{LBAS}}$)
4. Brakes ($E_{\text{BR}}$)
5. Sanding systems ($E_{\text{SAND}}$)
6. Lubrication systems ($E_{\text{LUB}}$)
7. Monitoring systems ($E_{\text{MONI}}$)

The consumption of Heating, Ventilation and Air Conditioning systems (HVAC) and other services to the passengers (“hotel services”) are not included in the previous list – although it is an important part of the energy consumption of a vehicle and can go easily over 15% of the total energy consumed – as it is not considered a running gear innovation. HVAC are by far the biggest energy consumer as they usually represent up to 80% of the “hotel services” consumption [40]. In any case, if the user wants to include it, it is always possible to account for this term as part of the $E_{OTHER}$.

The first three terms (1-3) are the ones having potentially more relative importance while the others (4-7) are not significant for the total energy consumed by the vehicle. The latter are however
important by influencing other running conditions which affect other modules in UCM2.0 (i.e. active steering in wheel wear)

Regarding active systems, they are divided broadly in primary and secondary based on where the actuation takes place, i.e. between the wheelset and the bogie, or between the bogie and the car body, respectively. The latter are also divided depending on their bandwidth response by differentiating low bandwidth systems (tilting, secondary lateral suspension centring systems) and high bandwidth where the actuators have a high frequency response. The scientific literature on this topic is extensive. An updated and excellent review can be found in reference [41]. The energy consumption of the proposed solutions is not always explicitly cited but it can be calculated once the vehicle, track and operation parameters are known.

When looking at vehicles with active suspension solutions, apart from including in the analysis the energy consumption of the system, it is important to keep in mind the effect that they have in improving other aspects. A simple example is tilting trains which is a solution widely adopted in certain routes where the orography of the country forces rather curvy tracks. Tilting trains take advantage of the fact that the speed through curves is principally limited by passenger comfort (in most cases a lateral acceleration of 0.65 m/s²). Tilting the car body on curves reduces the acceleration experienced by the passenger, which permits higher speeds and avoids reducing the speed before a curve and accelerating after the transition. This as a beneficial effect on energy consumption as shown in some experiences [42]. It is obvious that the speed increase has a limit as both maximum lateral forces on the track and the risk of overturning have to be considered. But overall speeds on curves may theoretically be increased by around 30% with tilting trains.

Regarding braking systems, an updated investigation and review can be found in [43]. The energy consumption of the braking systems itself depends on the selected technology but the relevant part is if regenerative braking exists which is discussed in the next subsection. Braking has obviously an effect on longitudinal train dynamics. A valuable tool for longitudinal dynamics analysis is available, TrainDy [122]. TrainDy is a UIC-approved software program that calculates longitudinal forces along trains. A key feature of TrainDy software is its capacity to solve both pneumatic problems (venting of brake pipe and filling of brake cylinders) and mechanical problems (computation of relative movement between consecutive wagons).

3.2.3. Energy refeed: Regenerative braking in UCM2.0

A train can decelerate by reversing the operation of its motors. During braking, the motors of a train act as generators converting mechanical energy to electrical energy. This recovered energy can be used internally in the train but there is usually an excess of energy which has to be managed in order to avoid over-voltages in the lines. There are three main options to tackle this:

1. Harmonising the loads of traction power supply lines, such as Train timetable optimization: this means synchronisation when a train is braking and feeding
regenerative energy back to another train which is simultaneously accelerating and absorbing this energy.

2. Energy storage systems (ESS: regenerative braking energy is stored on board the vehicle or wayside.

3. Reversible substation, in which a path is provided for regenerative energy to flow in reverse direction and feed power back to the main AC grid.

Studies that have been performed on train timetable optimisation can be classified, according to their objectives, into two main categories: minimizing peak power demand, and maximizing the utilization of regenerative braking energy [123]. Although this is a promising energy saving strategy, its application is more direct to metro systems. In order to attain such synchronisation, analysing driving strategies and optimising the railway timetables are mandatory. However, due to the constraints present in the transport market and safety regulations, optimisation of railway schedules and performance become difficult.

Reversible substations use power electronic inverters that enable bidirectional flow of current between substations and vehicles are required. However, attention has to be paid in supplying admissible power quality and avoiding possible transmission of harmonics pollution to the external grid. In addition, it must also address the challenges of their cost, complexity, and adaptability.

Storing the recovered energy using Energy Storage Systems (ESS) is a promising alternative to overcome the limitations of aforesaid solutions. Based on required functionalities of ESS, there are two types of installation of ESS such as stationary or on-board ESS.
Table 8. A comparison between different recuperation techniques in regenerative braking ([44]) ([44]) summarises the main advantages and disadvantages of the different options.

Table 8. A comparison between different recuperation techniques in regenerative braking ([44])

<table>
<thead>
<tr>
<th>Application</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onboard ESS</td>
<td>Provides possibility for catenary-free operation</td>
<td>High costs due to placement of ESS on the vehicle</td>
</tr>
<tr>
<td></td>
<td>Reduces voltage drop</td>
<td>High safety constraints</td>
</tr>
<tr>
<td></td>
<td>Reduces losses and increases efficiency</td>
<td>Standstill vehicles for maintenance and repair</td>
</tr>
<tr>
<td>Wayside ESS</td>
<td>Mitigates voltage dip</td>
<td>Increases overhead line losses due to the absorption and release of energy</td>
</tr>
<tr>
<td></td>
<td>Can be used by all vehicles running on same section</td>
<td>over the traction line</td>
</tr>
<tr>
<td></td>
<td>Maintenance and repair do not impact train operation</td>
<td>Analysis is required to choose the right sizing and location</td>
</tr>
<tr>
<td>Reversible Substation</td>
<td>Provides possibility for refeeding electricity to the main grid</td>
<td>No voltage stabilisation</td>
</tr>
<tr>
<td></td>
<td>Can be used by all vehicles running on the line</td>
<td>Analysis is required to choose the right location</td>
</tr>
<tr>
<td></td>
<td>Lower safety constraints</td>
<td></td>
</tr>
</tbody>
</table>

Reference [45] presents a novel tool for making a technical evaluation of the usage of onboard and stationary ESSs for a DC light rail vehicle’s network. The ESS optimal sizing, positioning, and control are determined, and their benefits assessed for the case study of a metro line in Brussels. Table 9 summarises some of the results.

Table 9. Comparison of stationary versus on-board ESS on a metro line case study

<table>
<thead>
<tr>
<th></th>
<th>Stationary</th>
<th>On-board</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base</td>
<td>Optimistic</td>
</tr>
<tr>
<td>Number of ESS needed</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>ESS usable energy capacity (kWh)</td>
<td>4.53</td>
<td>1.46</td>
</tr>
<tr>
<td>Total energy capacity needed (kWh)</td>
<td>27.18</td>
<td>80.3</td>
</tr>
<tr>
<td>Energy Savings. High traffic volume</td>
<td>11.7</td>
<td>19.6</td>
</tr>
<tr>
<td>Energy Savings. Moderate traffic volume</td>
<td>17.1</td>
<td>22.8</td>
</tr>
<tr>
<td>Energy Savings. Low traffic volume</td>
<td>25.7</td>
<td>29.3</td>
</tr>
</tbody>
</table>

Whatever technical solution is adopted to recover the energy, regarding UCM2.0, the term $E_{REC/FEED}$ is the amount of energy that will have a direct reduction in the energy cost. This means that the total energy consumed, $E_{TOTAL}$, minus the Energy refed, $E_{REC/FEED}$, is the energy that will have to be paid to the energy provider.
The following subsections provide a description of different Energy Storage Systems for railway applications [124]

3.2.3.1. Flywheels
A flywheel is a mechanical device which uses the conservation of angular momentum to store rotational energy. An electrical machine can either operate as motor to supply kinetic energy when a flywheel is charging or as generator to produce electrical energy when a flywheel is discharging the stored kinetic energy. Flywheel Energy Storage System (FESS) converts electric energy into kinetic energy and stores the same in a high speed rotor. The stored kinetic energy is then converted into electrical energy when necessary through connecting the rotor with an electrical machine via a bearing. In order to reduce the friction in the bearing, magnetic bearings are preferred due to its characteristics of magnetic levitation that causes frictionless rotation. For better controllability, active magnetic bearings seem a better option. However, they will have power losses due to its biased current. For zero input power requirement, passive magnetic bearings (PMB) are also used. Regarding electrical machines, they are classified as synchronous and asynchronous machines. In the case of synchronous machine, permanent magnet synchronous machines are widely used in FESS due to its high overall efficiency and generation of rotor flux by permanent magnet that causes low rotor loss. However, its significant demerits are high cost and low material tensile strength. In the case of asynchronous machines, Induction Motors (IM) are widely employed in high power applications due to its high torque capacity, robustness and cost reduction. IM design is more complex as the rotor used in IM requires the wires and electrical brush connectors and also due to its speed limitation.

3.2.3.2. Electric Double Layer Capacitors (EDLC):
In EDLC, the electrodes are soaked in an electrolyte, the electro-static charge formed at the interface between electrode and electrolyte, produces capacitance. During charging phase, the movement of electrons from positive to negative electrode causes gathering of cations and anions in the electrolyte in positive and negative electrode respectively. During the discharging phase, the electron transfer from negative to positive electrode, causes mixing of anions and cations once again. Activated carbon-based materials are widely utilised for the electrode due to its high specific surface area (1000-2000m2/g), high availability and low cost. Carbon material can either be activated by physical or chemical mixing. However, carbide derived carbon (CDC) material is preferred over carbon-based material due to its ability to optimise pore size of CDC structure that causes higher capacitance. In recent years, graphene based EDLC’s are mostly used due to its high cycle capability caused by the arrangement of single layer carbon atoms as honeycomb crystal lattice, excellent electrical conductivity, and thermal stability.

3.2.3.3. Battery based ESS:
Battery based energy storage systems store electricity in the form of chemical energy. Based on the type of chemical used in electrode, they are classified into following: Lead-acid batteries, nickel-based batteries, sodium-based batteries, lithium-ion batteries and redox-flow batteries.
a) Lead acid battery: The lead-acid battery based ESS is composed of: an anode made of sponge lead; a cathode made of lead dioxide; a separator to prevent short-circuit made of microporous membrane or an absorbed glass mat; and an electrolyte made of diluted sulphuric acid where the two electrodes and separator are immersed. In the discharging phase, the reaction between electrolyte and two electrodes (cathode and anode) produces lead sulfate and electrical energy. In addition, lead and lead oxide are produced through reaction between lead sulphate and water under external electrical energy. It is mostly used in low-cost applications due to its high reliability and technological maturity. However, if it is over-discharged, presence of large amount of sulfate crystals with bigger size causes more difficulty to break them during charging process and can even lead to short circuit. In order to overcome its demerits such as low energy density, and limited cycle capability, different variants of its configuration are developed such as valve-regulated, deep-cycle and advanced versions. In addition to above demerits, toxic nature of lead leads to imbalance in agricultural ecosystem caused by metal pollution during manufacturing and disposal stage.

b) Nickel based batteries: Nickel-cadmium batteries had huge market share until the arrival of nickel-metal hydride and lithium-ion batteries. In this type, nickel hydroxide-based anode, cadmium based cathode and electrolyte made of alkaline potassium hydroxide, are used. It is mostly used due to its following merits such as low internal resistance, high tolerance at high charge and discharge rates, broad range of operating temperature and rapid charging due to the occurrence of endothermic reactions during charging. However, Nickel-metal hydride based ESS are widely preferred in order to overcome the following demerits of nickel-cadmium batteries such as: high self-discharge rate and lifetime reduction of rechargeable battery charges due to incomplete discharging at previous usage (memory effect), more cell requirement to cope with the required voltage level due to its lower cell voltage than lead-acid and lithium-ion batteries, weak battery-pack balancing caused by the various self-discharge rates of cells and toxic nature of cadmium (heavy material). The major difference between nickel cadmium and nickel metal hydride battery is the hydride alloy-based cathode. Nickel metal hydride batteries also have the following merits such as better energy density, cycle capability, reduction of impact caused by memory effect and perfect balance in eco-system. However, functional separator is required to eliminate its major obstacle called high self-discharge rate which causes increase in complexity and cost of manufacturing.

c) Sodium-based batteries: The motion of sodium ions from anode to cathode operates the sodium-based batteries. Its cathode is made of molten sodium. The different variants of this battery are developed only by changing the materials used for anodes and electrolytes. In the case of sodium Sulphur battery (NaS), molten sulphur and solid beta alumina ceramic are used as anode and electrolyte respectively. NaS batteries are highly preferred due to its following merits such as high energy and power densities, no self-discharge, tremendous cycle capability and low cost. However, it also has significant demerit such as high operational temperature requirement (300ºC - 350 ºC). Sodium nickel chloride batteries (NaNiCl₂) have a higher cell voltage and better safety. However, it also has following
demerits such as: lower energy density than NaS batteries and high operational temperature range (270°C – 350°C).

d) Lithium-ion batteries (Li-ion) are widely used in small electronic devices and electric vehicles. Its charging operation is based on motion of lithium ions between anode to cathode whereas discharging operation is based on reverse motion of the lithium ions from cathode to anode. Li-ion batteries have higher cell voltage, higher energy density, charge efficiency and longer lifespan as compared to Lead-acid and nickel-based batteries. By adopting different materials for electrodes, different variants of this battery such as lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminium (NCA), lithium iron phosphate (LFP) and lithium titanate (LTO) have been produced. These batteries are broadly classified into two categories namely high-power batteries and high-energy batteries. LFP and LMO batteries are recommended for their high-power density which enables them to offer high current rate at discharging operation. As LFP batteries have almost flat discharge voltage curve, it enables them to deliver more stable power output with certain discharge current over the different state of charges (SOC). However, LFP batteries have the following demerits such as lower nominal voltage (3.2V) and low specific energy as compared to that of other Li-ion batteries (nominal voltage range 3.6V to 3.7V). Despite of having lower self-discharge rate as compared to that of Lead-acid batteries, LFP batteries have high self-discharge rate as compared to those of other Li-ion batteries. In the case of LMO batteries, it has higher specific energy and lower self-discharge rate than LFP batteries. However, its cycle capability is low. The combination of LMO with NMC batteries leads to overcome the above obstacles. A typical Nickel based Li-ion batteries are widely preferred due to their following merits such as higher specific energy, high cyclability and relative stability as compared to LFP and LMO batteries. However, utilizing cobalt material leads to increase in manufacturing cost.

e) In Redox (Reduction and oxidation flow batteries - RFB), electrical energy is produced through reduction and oxidation reaction between two active liquids which are separated by an ion-exchange membrane. The most common redox flow batteries are Vanadium redox flow batteries (VFRBs), poly-sulphide/bromine flow batteries and zinc/bromine flow batteries. These batteries have following merits such as excellent scalability, longer life cycle and size independency for energy and power. Storage of electrolyte in separate tanks leads to zero self-discharge in this kind of batteries. Its cell temperature can be easily handled through electrolyte-flow regulation. However, it also has some demerits such as solution precipitation caused by unsuitable operational temperature, low energy density and low power density. In order to overcome above limitation, it is recommended to maintain the operational temperature between 15°C – 35°C.

3.2.3.4. Hydrogen fuel cells:
An electro-chemical device that generates electricity through blending hydrogen fuel and oxygen is known as a hydrogen fuel cell (HFC). As conventional HFC can only generate the electricity without storing, it should be equipped with a hydrogen storage system in order to become a regenerative
system. In HFC, hydrogen produced by electrolysis of water is stored in pressurised storage system made of metal-hydride or carbon absorbers. As HFCs have following merits such as high energy density, moderate power density, non-toxic and very high scalability as compared to other types of ESS. It emerges as a potential ESS in electrified rail vehicles. However, demerits of HFC such as low efficiency (35%), high manufacturing cost, low discharge efficiency and operational temperature compatibility, will certainly compromise its usage.

3.2.3.5. Super-conducting Magnetic Energy Storage systems (SMES)
In SMES, flow of DC current in the superconducting coil generates a magnetic field where the electrical energy is stored in the form of magnetic energy. Maintaining the coil at super-conducting state is achieved through cooling the coil which is immersed in liquid helium/nitrogen into cryogenic temperature. During charging, electrical energy can be stored indefinitely due to zero degradation of coil current caused by zero resistance of coil at super-conducting state. While discharging, stored magnetic energy is again converted to electrical energy and delivered to external load. SMES’s have the following advantages: high energy efficiency, high power density, rapid charging/discharging and longest life cycle. They have the potential to be widely used as ESS. In this SMES, recent development of high-temperature super-conducting materials improves its performance and economic merits. However, they also have significant demerits such as their high manufacturing cost and the generation of huge electromagnetic forces.

3.2.3.6. Hybrid energy-storage systems (HESS)
The integration of at least two or more types of ESS device in order to cope high energy or high-power demand is known as HESS. The common types of HESSs are the following: passive parallel, cascade and active. In passive parallel configuration, two ESS systems are connected without employing any power electronic device (power converter combinations – DC-AC, AC-AC, and AC-DC-AC). Although its architecture is simple and easy to incorporate, the output voltage differs in the charge and discharge states. In the case of cascade systems, they are more efficient than passive parallel ones. However, they require a power converter between different ESS which leads to high cost, scalability issues and lacking freedom of control strategy. Among the three types of HESS, the active parallel systems have the maximum flexibility to operate at its optimal conditions and to attain maximum power point tracking through their specific power converter. Energy management strategies are also essential in the design of HESS.

3.2.4. Including CO2 emission costs in the Energy module of UCM2.0
The calculation of the CO2 cost is based on the greenhouse gas emission (g CO2e/kWh) from electricity generation in 2019, provided by the European Environment Agency [13]. The user chooses the country (or alternatively the average EU28) in the landing page and the corresponding emission value from electricity generation are then automatically combined with the CO2 cost at €1E-04 per g CO2e, which is the climate change avoidance cost (short-and-medium-run, up to 2030, in €2016) set by the European Commission’s handbook on the external costs for transport [8]. However, it should be noted that electricity generation is part of the EU Emission Trading System
(EU ETS) and can therefore (at least partially) be considered as internalised (see further information in sections 2.2.2 and 2.2.3).

3.2.5. Changes in the Energy module in UCM2.0

This section describes the proposal for the Energy Module in the UCM2.0. The development of the UCM2.0 beta version was carried out in parallel to these work packages, so the figures and structure are preliminarily defined. The final UCM2.0 tool will be structured in this way, but changes might arise throughout the review and testing process that modify one or more traits of the module. These modifications will be described in the final deliverable D1.3.

The Energy module has the same structure as other modules of the UCM2.0:

- On top of the page the total energy costs, this is the final result in €/year. As shown below there are three values. As explained in the UCM2.0 manual, the tool always uses reference values that come for the System Platform Demonstrators definition (SPD1 High Speed, SPD2 Regional Trains, SPD3 Metro vehicles), the columns in grey. The result in the grey cell (SPD) comes from the reference calculation carried out, the orange and yellow cells correspond to two different cases (Case 1 and Case 2) that the user is analysing.

<table>
<thead>
<tr>
<th>ENERGY MODULE</th>
<th>€/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPD Case 1</td>
<td>17,864,96 €</td>
</tr>
<tr>
<td>Case 2</td>
<td>16,680,75 €</td>
</tr>
<tr>
<td>Case 2</td>
<td>22,028,18 €</td>
</tr>
<tr>
<td>€/year</td>
<td>16680,75</td>
</tr>
</tbody>
</table>

**Figure 9. The UCM2.0 Energy module screen capture (2)**

- Performance inputs: These are the specific inputs that the module requires from preliminary calculations carried out by the user. In this case:
  - Total energy consumption running from A to B + B back to A, round trip (kWh), \( E_{\text{TOTAL}} \)
  - Energy refeed running from A to B and back to A (kWh), \( E_{\text{REC/FEED}} \). This needs to be inserted as a negative value.

**Performance Inputs**

<table>
<thead>
<tr>
<th>Total energy consumption running from A to B + B back to A (kWh)</th>
<th>SPD</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{\text{TOTAL}} )</td>
<td>27,93</td>
<td>25,00</td>
<td>32,00</td>
</tr>
<tr>
<td>Energy refeed running from A to B + B back to A (kWh)</td>
<td>0,83</td>
<td>1,00</td>
<td>3,00</td>
</tr>
</tbody>
</table>

**Figure 10. The UCM2.0 Energy module screen capture (2)**

- The Cost calculations provides a short explanation on how the calculations are carried out and provides also some intermediate results.
Cost Calculation

The module calculates the energy costs by adding the costs of the total energy consumption taking into account the energy cost and the Energy refeed, and adding the cost for CO2 emissions

\[ \text{Cost}_{\text{TOTAL}} = \text{Cost}_{\text{Total energy}} + \text{Cost}_{\text{Energy refeed}} + \text{Cost}_{\text{CO2}} \]

- Take into account that the energy refeed is input as a negative value
- The discount is only applied to the term Cost_{Total energy}

\[ \text{Cost}_{\text{Total energy}} = \text{Cost}_{\text{Total energy}} \times \text{averaged energy consumption rate} - \text{discount} \]

\[ \text{Cost}_{\text{Energy refeed}} = \text{Cost}_{\text{Energy refeed}} \times \text{averaged energy refeed rate} \]

\[ \text{Cost}_{\text{CO2}} = \text{Cost}_{\text{CO2}} \times \text{tons CO2/kWh} \times €/ton CO2 \]

The cost of CO2 emissions is based on the total energy consumed, the emissions (tonnes CO2) that the production of the generation produces and the cost of the emission of a tonne of CO2.

The total energy consumption running from A to B and back to A (ABA) is an input by the user to the module and has to include the rolling, gradient, rolling, aerodynamic and curve resistance. And, if considered relevant, other energy consumption terms such as: auxiliary components, tunnel resistance, unstable running, etc.)

It might be that the user has measured data on the consumption running ABA on similar vehicles. In this case this experimental value can replace the energy consumption calculations:

\[ E_{\text{TOTAL}} = E_{\text{RR}} + E_{\text{GR}} + E_{\text{IR}} + E_{\text{AR}} + E_{\text{CR}} + E_{\text{OTHER}} \]

Energy consumption terms

- Energy consumption due to rolling resistance (kWh) \( E_{\text{RR}} \)
- Energy consumption due to gradient resistance (kWh) \( E_{\text{GR}} \)
- Energy consumption due to inertia resistance (kWh) \( E_{\text{IR}} \)
- Energy consumption due to aerodynamic resistance (kWh) \( E_{\text{AR}} \)
- Energy consumption due to curve resistance (kWh) \( E_{\text{CR}} \)
- Energy consumption due to other (unstable running, auxiliaries, tunnel, etc.) \( E_{\text{OTHER}} \)
- Energy refeed (kWh) \( E_{\text{REC/FEED}} \)

Calculation options

The following inputs and options are used for the calculation of the Module costs.

Global Inputs

These are defined in the Case Selection page and cannot be modified here as they affect different Modules.

Vehicle characteristics and mission profile input

<table>
<thead>
<tr>
<th>Vehicle characteristics and mission profile input</th>
<th>SPD</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>annual travelling A-B-A</td>
<td>n_{ABA}</td>
<td>5000</td>
<td></td>
</tr>
<tr>
<td>track length (km)</td>
<td>tr_{leng}</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>seats per train</td>
<td>seats</td>
<td>350</td>
<td></td>
</tr>
</tbody>
</table>

Calculation options

- The Calculation options first part includes the global inputs, they are called “global” as they are used by other modules and consequently directly defined in the landing page (first page) of the tool. The user cannot modify the grey cells, but can change the values of the cells in Case 1 and Case 2. The SPD is kept as a reference to which the cases are compared.

- The Calculation options second part includes the Module inputs, they are specific to this energy module. Again, the user cannot modify the grey cells, but can change the values of the cells in Case 1 and Case 2. The SPD is kept as a reference to which the cases are compared.
3.2.6. The Module inputs of the Energy module in UCM2.0

The calculations of Energy costs are taking the approach used in Germany where a distinction is made between a high tariff (6 a.m. to 10 p.m.) and a low tariff (between 10 p.m. and 6 a.m.) for the electricity. Additionally, a discount is possible depending on the volume that the costumer purchases. It is described in [125].

Other tariffs schemes should be reconverted to this scheme for the calculations:

- In the UK Network Rail bases the tariff in this document [126]. It is calculated based on blending the delivery and the energy tariffs. The tariff applicable to charter EC4T usage in 2021/22 will be 12.425 pence per kWh. The next notification will be sent in March 2022 in relation to the tariff applicable in 2022/23
- In Sweden the electricity trading price can be found in this report [127]. The price used for debiting may vary depending on the proportion charged according to hourly rates.

The module inputs can be seen in Figure 13. The user should specify:

1. proportion of high energy consumption rate period (%). This is the train percentage of energy use in the high tariff day period
2. high energy consumption rate (€/kWh). This is the price of electricity in the high tariff day period
3. low energy consumption rate (€/kWh). This is the price of electricity in the high tariff day period
4. proportion of high energy refeed rate period (%). This is the train percentage of refeed energy use in the high tariff day period.
5. high energy refeed rate (€/kWh). This is the price of electricity refeed in the high tariff day period
6. low energy refeed rate (€/kWh). This is the price of electricity refeed in the low tariff day period

**Figure 13. The UCM2.0 Energy module screen capture (5)**

<table>
<thead>
<tr>
<th>Energy cost calculation input</th>
<th>SPD</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>proportion of high energy consumption rate period (%)</td>
<td>per_hEC_rate</td>
<td>0,3</td>
<td></td>
</tr>
<tr>
<td>high energy consumption rate (€/kWh)</td>
<td>hEC_rate</td>
<td>0,125</td>
<td></td>
</tr>
<tr>
<td>low energy consumption rate (€/kWh)</td>
<td>lEC_rate</td>
<td>0,106</td>
<td></td>
</tr>
<tr>
<td>proportion of high energy refeed rate period (%)</td>
<td>per_hER_rate</td>
<td>0,45</td>
<td></td>
</tr>
<tr>
<td>high energy refeed rate (€/kWh)</td>
<td>per_hER_rate</td>
<td>0,06</td>
<td></td>
</tr>
<tr>
<td>low energy refeed rate (€/kWh)</td>
<td>lER_rate</td>
<td>0,048</td>
<td></td>
</tr>
<tr>
<td>discount</td>
<td>dis_rate</td>
<td>0,06</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>These are specific for this module and the user can thus insert own values here:</td>
</tr>
<tr>
<td>Energy cost calculation input</td>
</tr>
<tr>
<td>-------------------------------</td>
</tr>
<tr>
<td>proportion of high energy consumption rate period (%)</td>
</tr>
<tr>
<td>high energy consumption rate (€/kWh)</td>
</tr>
<tr>
<td>low energy consumption rate (€/kWh)</td>
</tr>
<tr>
<td>proportion of high energy refeed rate period (%)</td>
</tr>
<tr>
<td>high energy refeed rate (€/kWh)</td>
</tr>
<tr>
<td>low energy refeed rate (€/kWh)</td>
</tr>
<tr>
<td>discount</td>
</tr>
</tbody>
</table>
As explained before, if the user does not specify any values for the module inputs in Case 1 (orange colour cells) or Case 2 (yellow colour cells), the calculation will be based on the SPD values (grey colour cells).
4. UCM2.0 Noise Module

The activities described in this section correspond to Task 1.3, which objectives were

- Review the state-of-the-art on calculating the marginal cost of noise and include the influence of noise in the LCC analysis.
- Overview of the regulations and valuations currently used at the EU level and EU member countries, including the European Commission’s handbook on external costs of transport.
- Comparison of these regulations to theoretical models for external noise emissions.
- Development of a UCM module to define noise emissions cost from an actual vehicle.

Regarding the analysis on how to include comfort issues,

- Review the state-of-the-art on valuations of noise and vibration in rail vehicles and propose a method to include noise issues for passengers in the UCM.
- Analysis of the influence of the ‘packaging effect’ for the subjective passenger comfort valuations.

Noise is a major concern in many developed countries and causes not only disturbance but also adverse health effects. According to the European Environmental Agency (EEA), railways are the second largest noise polluter after road traffic in terms of number of affected people. In Europe, around 19 million people are exposed to railway noise above 55 L_{den}^1 [55]. This is above the WHO guideline value of 54 L_{den} which represents the limit when negative health impacts occur [56]. To address the problem related to noise, the European Commission has adopted the Environmental Noise Directive 2002/49/EC (END). It instructs EU members to map noise levels for cities, roads, railways, and airports, and to develop an action plan on how to manage the problem.

Several European countries have implemented regulations that restrict permissible noise levels at buildings and houses. For example, the Netherlands have introduced so-called ‘preferred limit values’ which are noise levels near buildings that, if exceeded, require official exemptions, and ‘maximum exemption values’ which are only allowed in exceptional circumstances [57]. Another measure introduced by the Netherlands, Germany, and Switzerland is noise-differentiated track access charges (NDTAC) that force operators of ‘noisy vehicles’ to pay a penalty in form of a surcharge. These charges can contribute to a more efficient use of the railway infrastructure since noise from rail traffic is an external cost. In addition, noise charges create incentives to invest in new and more silent technology as for example retrofitting of freight vehicles from cast-iron to composite brake blocks. [59], [60] To motivate this type of investment, its impact on noise costs

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1 L_{den} (day-evening-night level): A noise level of European standard based on the equivalent noise level (Leq) over a whole day with a penalty of 5 dB(A) for evening noise (19.00-23.00) and a penalty of 10 dB(A) for nighttime noise (23.00-7.00) [58]
(and on any charges) needs to be calculated along with other effects. This is an important aspect of UCM2.0 which aims to quantify the value of innovations in running gear.

The following subsections on noise present a review of the state-of-the-art on methods for calculation of marginal costs of noise, as well as an overview of European guidelines for transport appraisals of costs due to railway noise. The aim is to provide a basis for the new noise module in the UCM2.0. Here it can be noted that the impact on noise costs during the life cycle of the train/running gear is the final output of this module. Yet, the marginal cost of noise is a key input since the train will operate in an environment that is already exposed to noise, be it from other trains or other noise sources such as road transport, and the impact of extra noise indeed depends on the current noise level.

4.1. Railway noise

Railway noise originates from different sources in the vehicle–track system. Figure 14 illustrates how the dominant railway noise type/source vary with vehicle speed. For most speeds, noise radiated from wheel and track superstructure (i.e. rails and sleepers/slab) due to excitation from acoustic rail and wheel roughness, so called rolling noise, dominates. Aerodynamic noise radiated due to air flow around, for example, pantographs and bogies become significant at vehicle speeds that exceed approximately 200 km/h. This limit in vehicle speed also implies almost a doubling in rate of noise increase with respect to vehicle speed (see Figure 14). Power equipment noise, also known as traction noise, originates from engines, fans, exhaust outlets and traction motors, and is the dominating noise source at low vehicle speeds and at stand-still.

Other types of railway noise are radiated at specific locations along the track network. To this category belongs curve squeal, bridge noise and impact noise. In strategic noise maps these locations are termed ‘hot spots’ and accounted for by specially adapted procedures [61]. Curve squeal is loud, strongly tonal and generated at a high frequency. The conical wheels rigidly attached by the wheel axle enables railway wheelsets to negotiate curves. This so-called radially steering capability deteriorates when the difference in rolling radii between the outer and inner wheels cannot fully compensate for the longer running distance of the outer compared to the inner wheel. As a result, curve squeal may develop. Apart from the vehicle curving ability, curve radius is the single most important variable with regard to curve squeal probability. Curve squeal primarily occurs in curves of radius below 500 m [62]. On a bridge, the train interacts with a structure that has significantly different dynamic behaviour and noise radiating characteristics compared to track at grade. That makes bridge passages associated with an increase in radiated noise of typically about 10 dB particularly concentrated in the low frequency range. Impact noise represents the final location specific railway noise source and is caused by discontinuities on the wheel and rail running surfaces, generated for example at turnouts and insulated rail joints. It has been shown that the discrete time-instance of noise makes the evaluation of annoyance by calculating pass-by noise levels insufficient [63].
In contrast to other types of railway noise, rolling noise is not specific to location along the track network (e.g., curve squeal, bridge noise) or vehicle type (e.g., aerodynamic noise only emitted by high-speed passenger trains only). This makes rolling noise the most important noise source in the rail bound transportation system [64], [60]. Measurements of rolling noise published in literature by different research groups is collected in [65]. The impact of vehicle type on radiated noise levels is investigated and, in principle, results fall into two categories dependent on the type of friction brake mounted on the train: trains with cast-iron brake blocks and those with disc-brakes or composite brake blocks. In the measurement data, noise from the former vehicle category exceeds that of the latter by approximately 10 dB. This is the reason why freight trains equipped with cast-iron brake blocks is considered as the most significant current issue with respect to railway noise generation [66], [60], [64]. The root cause of the increased noise levels emitted by wheels with cast-iron block brakes is periodic wear (corrugation) that develops on the wheel tread which in turn causes increased magnitude roughness excitation during rolling. In 2018, about 75 % of the European freight wagon fleet was equipped with this type of brake blocks [67]. Passenger rolling stock is usually equipped with disc brakes and rarely operates by night which makes them less of an issue than freight trains [67], [68].

It is fundamental in noise mitigation to identify the dominant source. Rolling noise is generated due to excitation by the combined wheel and rail roughness. As discussed above, for the case of freight trains equipped with cast-iron brake blocks, increased rolling noise levels are typically caused by large magnitude wheel roughness. For this situation, grinding to reduce rail roughness magnitudes will have a moderate impact on the radiated noise. On the opposite, similar pass-by noise levels have been measured for disc-braked passenger trains and freight trains equipped with cast-iron tread brakes when travelling on rails exposed to large magnitude roughness (i.e., corrugation) [69]. The later corresponds to a case when the combined wheel–rail roughness is instead dominated by the rail surface irregularity. For traffic consisting of vehicles with disc-brakes and/or composite tread brake blocks, the maximum potential noise reduction obtained with rail grinding is approximated to 5 dB [66]. During rolling, the surface roughness of wheels and rails induce vibrations of the vehicle–track system that in turn generate rolling noise. To this end, both wheels and rails make significant contributions to the total radiated noise. In general, with respect to noise radiation, the rail is important for all frequencies whereas the wheel makes a substantial contribution in the high frequency range (above 1 kHz) [62]. Moreover, the relative contribution of vehicle and track on the emitted noise shows a speed dependence where an increase in vehicle speed causes the noise radiation to shift from rails to wheels [65].

Acoustic grinding of rails and reprofiling of wheels are examples of noise mitigation at source. For these measures to be effective, they need to be subjected to the dominant noise source. There is no universally applicable noise control method since the contribution of the vehicle and track to the total emitted noise depends on mechanical (e.g. design of track superstructure) and operational (e.g. vehicle speed, type of train) properties as well maintenance status (e.g. surface roughness). Instead, measures need to be tailored with respect to conditions at the particular field site. Other examples
of actions to reduce noise radiation at source are attenuation of wheel and rail vibration by attaching dampers or by modifying rail pad properties. If mitigation at source is not possible, the next step is to assess the propagation path of the dominant noise source(s), i.e. noise barriers. These can be of different heights and mounted at trackside or on the vehicle as bogie shrouds. The combination of low height barriers mounted close to the rails and vehicle mounted shrouds has shown noise reductions of up to 10 dB(A) [70]. Finally, noise reduction can be achieved by measures at the receiver for example by installation of soundproof windows.

![Figure 14. Dominant sources of railway noise as function of vehicle speed [71]](image)

### 4.2. Calculating the (Marginal) Cost of Noise: An Overview

Traffic noise such as rail noise is experienced as a disutility and thus gives rise to external costs, which are third party costs that need to be taxed or regulated to contribute to an efficient use of the infrastructure. The two main impacts of noise causing disutility are 1) annoyance, which reflects the disturbance individuals experience when exposed to noise, and 2) health impacts such as ischaemic heart disease; stroke; dementia and hypertension [8], [10]. Annoyance is measured differently than the health impacts caused by noise. However, it is important to note that the two impacts are not necessarily independent since annoyance may lead to irritation, anxiety, and sleep disturbance which subsequently may lead to detrimental health effects. [72] This is further discussed in section 4.2.2.

Measures to reduce traffic noise are often costly to implement and may – as previously mentioned – include investments such as noise barriers and façade insulations, more frequent grinding of rails and repprofiling of wheels, as well as regulations on maximum noise emission level, speed limits, and retrofitting of freight wagons. Therefore, the disutility caused by noise needs to be monetised to compare the cost against the benefits of implementing such a measure in a cost-benefit analysis.
A CBA is an effective tool to guide resource allocation, however, it requires that both the costs and benefits are expressed in a common metric, usually in monetary terms. Thus, the benefits of reduced noise need to be monetised [73].

The impact pathway approach (IPA) is a methodology often used to calculate costs for air pollution and noise, and is described in section 4.2.1. An important part of the methodology is to put a monetary value on noise and there are different methods that can be used, which are described in section 4.2.2. Rail passengers also experience noise and may – along with other comfort issues – play a role in their demand for the service. Research on valuation of comfort issues such as noise and vibration experienced by passengers is described in section 0.

### 4.2.1. The impact pathway approach

The impact pathway approach IPA was first developed to investigate adverse health effects due to air pollution but has later also been applied to study noise exposure [74], [75]. The approach has been adopted by the European Commission’s Handbook on the external costs of transport to evaluate the detrimental impacts caused by noise [8]. The main steps in an IPA for railway noise are presented in Figure 15. The first step is to quantify the noise emission at the source, i.e. radiated noise levels. Secondly, the number of people exposed is assessed, for example by projection based on noise maps. Thereafter, endpoints or impacts of railway noise are assessed, where so-called dose-response functions are used to measure the relationship between noise exposure and a selected impact such as health effects, e.g. cardiovascular mortality. Finally, the cost of these effects is estimated in monetary terms.

IPA has already shown useful to assess health impacts. For example, using a consistent method like the IPA enables the identification of various impacts caused by noise and thus provides an overview of the effects. Another advantage is related to the dose-response functions which clarify the relationship between exposure and health impacts [74], [75]. Limitations in applicability are mainly associated with data issues, such as uncertainties on traffic flow and population density, and a lack of noise level data which, for example, can imply that information on the $L_{den}$ metric (equivalent noise level for day-evening-night) must be used when assessing sleep disturbances instead of the more appropriate $L_{night}$ metric. [75]
4.2.2. Valuation of noise

Individuals’ preferences are the most important benchmarks to monetise external noise costs. One method is the willingness to pay (WTP) for a noise reduction. Another method is the willingness to accept (WTA) compensation (in monetary terms) for non-improvement [10]. WTP is the method typically used to monetise noise, and this section therefore focuses on that method.

WTP (and WTA) only accounts for individuals’ preferences and are thus used to monetise the cost of annoyance effects caused by noise [8], whilst other approaches – e.g., disability-adjusted life year (DALY) and Value of a life year (VOLY) – are used for the cost of adverse health effects, such as cardiovascular disease, hypertension, and higher blood pressure [56]. However, annoyance and health impacts are closely linked. For example, annoyance may lead to sleep disturbance and higher stress levels which subsequently may cause negative health impacts. Since the effect of annoyance may overlap with some health impacts caused by noise, there is a risk for double counting the cost of noise, which is further described in section 4.2.2.1 below. Note also that, when valuating health cost, the methods VOLY and DALY can be based on the individual’s WTP for one additional year of life expectancy [8].
The following subsections on valuation will describe and discuss the main methods used to monetise the cost of noise: one subsection on annoyance effects and one subsection on health effects.

4.2.2.1. Valuation of annoyance effects
There are generally two approaches to monetise individual’s preferences: Revealed preference (RP) and stated preference (SP) methods. The RP method is an indirect approach which uses information on individual’s actual decision when estimating WTP, whereas the SP method is based on hypothetical markets, rather than actual decisions, by using for example surveys [10], [77].

One revealed preference method is the hedonic pricing approach which is used to examine the effect of noise level on property prices to estimate the willingness to pay (WTP) for noise mitigation actions. The technique was developed by [78] and is widely used to value non-market goods such as noise. The hedonic regression technique can be used to derive a property price function that accounts for the influence of several variables on the price of a property. According to [78], the property price depends on intrinsic attributes such as living surface area, number of rooms etc., and extrinsic attributes such as noise. The hedonic price function is given by:

\[ P = P(L, A) \]

where \( P \) denotes the price of the property, and \( L \) and \( A \) denote noise level and a vector of other extrinsic and intrinsic variables. [78] showed that the marginal WTP for a specific attribute equals the marginal rate of substitution between the price of the good and the attribute, hence the slope of the price function can be used to estimate the marginal WTP [78], [79], [73], [80].

Hedonic pricing has been widely used to assess the cost of traffic noise, and many appraisal guidelines focus on studies using this method. For example, the marginal cost of railway noise in Swedish transport appraisals is mainly based on a study by [73] in which the hedonic pricing method was used in combination with data from various municipalities in Sweden on prices and attributes of properties of single-family houses. Environmental railway noise levels were estimated based on traffic and geographical information. Indeed, noise influences property prices negatively. However, it was found that individuals have no WTP for noise mitigation actions for noise levels below 49.1 dB. Overall, the results suggest that a 1 dB reduction of railway noise levels lead to a welfare gain that corresponds to 162 USD per individual per year. Interestingly, individuals’ preferences of noise were found to vary significantly between different areas. A similar study [79] found that a 1 dB increase in noise level is associated with a 0.4 % decrease in housing prices. However, they used a threshold of 50 dB, hence using observations with a noise level equal to or above 50 dB and their noise coefficient was only significant at the 10% level. A study conducted in Birmingham, UK, found that a 1 dB increase in rail noise reduces the property prices by 0.67 % [81].

The hedonic pricing method is sensitive to the conditions of local housing markets, and the implicit price is sensitive towards the model specification. For example, if some external effects of
transportation such as pollution are not accounted for, the estimated impact of rail noise on housing prices can include these effects and be overestimated [82].

In SP methods for noise valuations, individuals are asked about their WTP for noise abatement. The method enables control over experimental conditions, where the noise levels can be controlled and decided, which is not possible in a real-life setting. Additionally, using hypothetical decisions avoids measurement errors of independent variables since it allows to assess the influence of different variables separately. Another major advantage of the SP compared to the hedonic pricing (RP) method is that the information used to estimate the cost of noise is obtained at the level of the decision maker, resulting in more precise estimates and multiple responses per decision maker can be obtained [83]. However, using hypothetical decision might not reflect an individual’s actual decision, which is a major drawback of the SP method. Additionally, like the hedonic pricing method, the SP method is a WTP assessment, and as such may not include all health aspects of noise. [84]

Valuations of railway noise by SP methods are few [85], [86], [87]. Still, a meta-analysis [83] on SP methods found that the value of railway noise varies significantly between different studies. This is also the case when comparing results from different countries, as found by [82]. Moreover, the results in [82] indicated no significant difference between WTP for railway noise in rural and urban areas.

A comparative study of the SP and hedonic pricing (RP) method in valuating road and railway noise is carried out in [86]. The SP method was suggested to result in a higher noise cost compared to that of the hedonic pricing method. However, this higher noise cost may be because almost all railways are equipped with passages, tunnels, or screening (walls or banks), and their noise reducing benefits are not reflected in the SP method.

4.2.2.2. Valuation of health effects

The WTP method only accounts for individuals’ preferences and may not include all health effects associated with railway noise. Other methods are therefore used to quantify adverse health effects associated with noise exposure including cardiovascular disease, hypertension, cognitive impairment, sleep disturbance, and higher blood pressure. There are in general two types of health effects of noise: 1) the effect on the individual such as pain or discomfort, and 2) the effects on the society which is the medical costs associated with the health effects [8], [72]. Medical cost considers not only the costs related to medical care but also the costs of productivity loss due to illness, e.g. working days lost.

To enable a monetization of the health effects of noise, the relationship between noise and health impacts needs to be considered. There is an extensive literature on the detrimental health effects caused by noise [72], [88]. However, the relation between noise exposure and health impacts is complex and difficult to investigate. For example, the sensitivity with respect to noise exposure can vary substantially across the population. In [75] it was found that individuals that have grown up in
rural/quiet areas were more sensitive towards noise than individuals raised in urban/noisy areas. It is therefore important to consider noise level and variations across the population to quantify the health effects of noise.

One approach to quantify effects from noise exposure on human health is the disability-adjusted life years (DALY) which is the sum of the potential years of lost life due to premature death or a healthy life lost due to poor health or disability [72]. DALY represents a dose-response function for noise exposure and health effects, and this relationship can take different shapes [89], [88], [72]. For example, some health effects may occur above a specific threshold or may not increase linearly with the amount of exposure [75]. Furthermore, the DALYs approach consider the exposure of the population to noise yet requires detailed data that might not be available.

The Value of a Life Year (VOLY), also known as the Value of One Lost Year, is the amount individuals are willing to pay for one additional year of life expectancy. Thus, VOLY is appropriate to use in circumstances of non-instantaneous deaths, for instance in the case of traffic noise exposure since the impact of noise on health is the cumulative result after years of exposure [90], [8].

Noise and other comfort issues for rail passengers

Comfort and ride quality are subjective and have a complex relation to many different aspects of travel. In addition to noise and vibration, factors such as seating, decor, temperature/ventilation, and toilets are important. It is therefore difficult to isolate the impact of noise. Moreover, the ‘packaging effect’ makes the valuation of a package of improvements less than the sum of each individual improvement [91], [92].

Challenges associated with noise measurements inside vehicle compartments are addressed in [93]. Interior noise levels show a weaker dependence on vehicle speed compared to external noise. Moreover, noise levels are noticed to vary significantly with rail surface roughness, measurement location inside the vehicle, type of vehicle, and weather conditions. This makes it difficult to provide a standardised method for interior noise measurement in rail vehicles. [93] provides a discussion on the difficulty to develop a standard that can capture the varying conditions that are representative for the passengers’ experience during typical train journeys.

An attempt to valuate train passengers’ perception of new or refurbished rolling stock is made in [91]. A major concern in this work is the packaging effect mentioned above. This makes the valuation of specific attributes such as noise difficult. The valuation is performed using a RP approach and a SP approach. In the SP approach, the noise level is accounted for on a categorical scale such as “very noisy, noisy, quiet and very quiet”. The passengers found seating comfort, ride quality, and ambience coefficients to be more important than noise, layout, and ventilation variables. However, a packaging effect was found in [91], making it difficult to draw a firm conclusion regarding the individual effects of the attributes.
A recent meta-study by [92] investigates the valuation of specific attributes for passengers’ ride comfort in rail vehicles. Existing research on public transport customer amenities is reviewed. The study includes 57 separate research publications and a total of 556 separate public transport customer amenity values. The investigations included in the study span between years 1993 and 2013 and are performed in 6 different countries (Australia, India, New Zealand, Norway, Sweden, and United Kingdom). Among these investigations, the SP approach is most common, but RP, customer ratings, and maximum difference scaling are also used. Issues associated with the valuation of amenities such as the ‘packaging effect’ are discussed. The influence of interior noise on passenger ride comfort is not evaluated separately. Results indicate a lack of work made on tram/light rail traffic system as compared to buses and trains/metro. Moreover, [92] find that a majority of valuations of amenities in public transportation are more than 10 years old.

The establishment of an assessment model for rail vehicle comfort and safety from passengers’ point of view is investigated in [94]. Several indices to quantify passengers’ comfort in terms of noise, lighting, vibration, and CO₂ concentration are identified based on a case study from the Montreal metro network. For verification purposes, a questionnaire survey was conducted on the Montreal metro. The perception of ride comfort is found to vary between customers depending on factors such as age, gender, and other socio-economic characteristics. Hence, there is no ideal comfort characteristic that would satisfy everyone. The difference in perceived comfort and safety in old and new rail vehicles were moderate. This was the case despite a significant difference in terms of interior noise levels. Younger passengers in both old and new vehicles showed a larger tendency to complain on interior noise compared to older passengers. The study [94] suggests that, although many aspects of modern rail vehicles represent improvements compared to their precursors, the acoustic comfort can still be further developed.

Overall, the studies presented in this section highlight issues and challenges related to the valuation of noise and other attributes for passengers in rail vehicles. The studies present noise on a categorical scale such as “very noisy, noisy, quiet and very quiet” and do not express noise level in a metric unit such as decibel scale. Consequently, this makes it difficult to interpret and apply the results of the studies in the UCM2.0. Further research therefore needs to be conducted to provide values that could be related to a metric scale to enable the result to be more applicable.

4.3. VALUATIONS AND REGULATIONS IN TRANSPORT APPRAISALS

To date, there is no standardised approach to the valuation of noise. As a result, appraisals across Europe vary significantly with respect to noise valuations and consider various aspects of noise. Section 4.3.1 discusses differences and similarities in the approaches used by transport appraisals in Sweden, UK, Germany, and Denmark. In addition, the studies and methods that these appraisals are based on will be briefly explained. Section 4.3.2 describes the estimates provided by the European Commission’s latest handbook on the external costs of transport [8].
4.3.1. Noise valuations in transport appraisals

Willingness to pay (WTP) is the approach used in most appraisals. The main method used within this approach is hedonic pricing, which (indirectly) estimates individuals’ willingness to pay as described in section 4.2.2. A major issue with monetizing the effect of noise by the WTP approach is that it only considers individual’s preferences, thus only the annoyance aspect and the health aspects that the individuals are aware of. It can also be difficult to distinguish between the health impacts that individuals are aware of and those they are unaware of. Despite this difficulty, most of the existing appraisal guidelines account for these effects separately. For example, the UK, Danish and Swedish appraisal include estimates of the amenity value separately in their valuation [84], [95], [29], [36].

The Swedish guidelines on appraisal of noise [84] consider the train characteristics such as speed, braking system, train type and length of train to calculate the marginal cost of noise and differentiate the marginal cost between 12 train types. Similarly, the German appraisal differentiate between train types, although they only differentiate between freight trains and passenger trains. Nevertheless, not all appraisals in other European countries present marginal noise costs for different train types, for example, the UK, which however provide a detailed transport noise modelling tool that can be used to calculate the marginal costs (and total costs) of noise impacts [96].

The health effects of noise can be valued and accounted for in various ways. The UK appraisal includes health issues associated with noise such as dementia and stroke as well as sleep disturbance separately [95] and the German appraisal separate the cost of psychological and cognitive effects from physical effects caused by rail noise [29]. The Swedish appraisal does not separate between specific health effects of rail noise but use a marginal cost for the general health effect caused by rail noise [84].

The Swedish, UK and German appraisals focus on the amenity value of noise. However, the Danish appraisal monetise the adverse health effects by the using health care cost and sick leave associated with the noise, and Sweden and UK do use the shortage of the life span caused by noise along with the amenity value.

Another key factor is to consider the noise level where noise starts to generate adverse health effects or cause disturbance. The threshold has been higher for rail than for road, where rail was given a “bonus” of 5 dB. Lately, this “rail bonus” has been questioned, and the EU’s handbook on external costs of transport [8] (see section 4.3.2 below) decided to abolish it since several studies reported rail noise to generate even more annoyance than road [97], [98], [99], or similar physical effects [100]. The varying evidence on when rail noise starts creating annoyance or adverse health effects has had an impact on transport appraisals. For example, the UK appraisal starts valuating noise above 45 dB whilst the Swedish noise appraisals start valuating noise at 50 dB.
There are several possible explanations for differences in noise valuations in transport appraisals. One explanation is differences in geographical location, which is mentioned as an important factor in the Swedish guidelines on transport appraisal [84]. Indeed, the marginal cost can vary in different regions and certainly between countries, since the WTP for noise abatement between individuals can differ significantly. One explanation for the heterogeneous response is that there may be partial habituation of noise, hence, the level of annoyance caused by noise can diminish with prolonged exposure. Individuals who grow up in rural areas may therefore be more sensitive towards noise exposure. The variations of individuals’ response to noise may lead to self-selection and potential biases since for example individuals with a high sensitivity are less likely to live in noisy areas [75].

Most of the appraisals, e.g., in UK and Sweden, are based on the hedonic pricing method which consider individuals’ willingness to pay for noise abatement by using housing prices to estimate the cost of noise (with the drawback that it only reflects the amenity effect of individual’s WTP). It is important to note that these appraisals do include a separate cost for health effects that is not accounted for in the amenity cost of noise.

There are some effects caused by rail noise that are not monetised in any of the mentioned appraisals, for example the material damages caused by vibration of rail noise (see also section 0 for valuation of noise vibration for rail passengers). According to the Swedish appraisal, research regarding the valuation of noise vibration is limited and they have therefore not monetised this type of disutility from noise. Other examples are the effects on the ecosystem due to behavioural changes among animals, e.g., disturbing the breeding pattern of birds [75], or effects on productivity where rail noise may cause tiredness and thus reduced quality of work. These effects are very difficult to valuate and are therefore usually not included in appraisals.

A comparison of these appraisals indicates that the valuation of noise centres around the amenity value, which is only one aspect of the negative impact of rail. Furthermore, the comparison shows the lack of a standardised approach to noise valuation amongst European countries. There are also other aspects that are not even monetised in current appraisals and more research needs to be conducted to be able to valuate for example the reduced productivity and the disturbance of the ecosystems that rail noise could be accountable for.

4.3.2. Noise valuations in the European Commission’s handbook

The European Commission has published a handbook on the external costs of transport [8] which includes estimates on the marginal cost of rail noise in Europe. These are based on the calculations made in [104] and [105] and updated using the development of average noise costs over time. Some of the input parameters are listed in [105]. For example, the number of affected inhabitants per km of track is 50, 250, and 3000 for rural, suburban, and urban areas, respectively.

Table 10 presents the marginal cost of rail transport per vehicle-km (vkm) reported in the handbook, which are average values for EU. As shown by Table 10, population density is taken into account
(i.e. the amount of people exposed to noise) by differentiating marginal costs for the area types metropolitan, urban, and rural. Furthermore, the costs vary with traffic volume, and thus the existing noise, where the marginal cost of an additional vkm when traffic is dense is lower compared to when traffic is thin. Here it can be noted that the relationship between traffic and noise is logarithmic, which means that the current level of noise is important when calculating a marginal effect. For example, as noted in [8], increasing the traffic volume from 50 to 100 vehicles per hour will have the same impact on the noise level as increasing the traffic volume from 500 to 1000 vehicles per hour, and hence the marginal effect (impact per extra vehicle) is very different in the two situations.

In addition, the handbook [8] report costs for three types of rail vehicles, each with a different cost for day and night since noise during night-time cause sleep disturbance and therefore results in a higher marginal cost. This is based on the \( L_{DEN} \) metric, comprising the noise levels \( L_{day} \), \( L_{evening} \) and \( L_{night} (L_{DEN}) \) where noise during evenings is treated as 5 db(A) louder, and noise during night-time are treated as 10 db(A) louder.

<table>
<thead>
<tr>
<th>Traffic situation</th>
<th>Metropolitan</th>
<th>Urban</th>
<th>Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High-speed train</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day Dense</td>
<td>38.0</td>
<td>21.2</td>
<td>3.1</td>
</tr>
<tr>
<td>Thin</td>
<td>62.4</td>
<td>34.7</td>
<td>5.0</td>
</tr>
<tr>
<td>Night Dense</td>
<td>69.2</td>
<td>38.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Thin</td>
<td>113.6</td>
<td>63.2</td>
<td>9.2</td>
</tr>
<tr>
<td><strong>Inter-regional passenger train</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day Dense</td>
<td>59.7</td>
<td>26.3</td>
<td>3.8</td>
</tr>
<tr>
<td>Thin</td>
<td>97.9</td>
<td>43.2</td>
<td>6.3</td>
</tr>
<tr>
<td>Night Dense</td>
<td>108.7</td>
<td>47.9</td>
<td>6.9</td>
</tr>
<tr>
<td>Thin</td>
<td>178.3</td>
<td>78.7</td>
<td>11.4</td>
</tr>
<tr>
<td><strong>Freight train</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day Dense</td>
<td>67.7</td>
<td>26.8</td>
<td>3.9</td>
</tr>
<tr>
<td>Thin</td>
<td>89.2</td>
<td>44.0</td>
<td>6.4</td>
</tr>
<tr>
<td>Night Dense</td>
<td>123.4</td>
<td>48.8</td>
<td>7.0</td>
</tr>
<tr>
<td>Thin</td>
<td>202.4</td>
<td>80.1</td>
<td>11.6</td>
</tr>
</tbody>
</table>

Source: [8]

4.3.3. Noise regulations

Regulations to reduce noise is one way to address the problems that railway noise causes. There are numerous measures that have been implemented to address the problem of railway noise. This section will discuss these measures and to what extent these measures may internalise the cost of noise according to current appraisals.

Rolling noise emissions from freight trains can be reduced by retrofitting from cast-iron to composite brake block material. The associated potential reduction in pass-by noise is approximately 8 dB(A) [60]. However, retrofitting of freight trains constitutes a significant
investment which also has subsequent economic effects in terms of increased maintenance needs as the composite brake blocks wear out quicker [67]. To create incentives for operators of rail freight to reduce noise emitted from their rolling stock, Germany, Switzerland, and the Netherlands have introduced noise-differentiated track access charges (NDTAC) for freight wagons. Freight trains with cast-iron brake blocks are labelled as “noisy wagons” and a penalty in form of a surcharge is incurred. Conversely, freight trains that have been retrofitted with composite brake blocks receive a bonus [59], [60]. Likewise, Austria has introduced a so-called noise bonus, whereby railway undertakings can receive a discount on infrastructure charges if they use retrofitted freight wagons, which thus creates an incentive to retrofit wagons with low noise braking technology [101].

By implementing a measure such as the NDTAC, the external cost of noise caused by trains can be internalised. This should take into account that the cost of noise varies with the noise level and the number of individuals exposed to noise at a particular track section [60], [84], [95]. In addition, annoyance caused by noise depends on the time of the day, where sleep disturbance makes railway noise emitted during night-time especially severe [60]. According to [102], there is evidence to support the hypothesis that exposure to noise during night-time might be associated with cardiovascular effects. Hence, the internalization of railway noise varies depending on conditions such as number of people exposed and time of the day. However, the NDTAC does not consider these conditions and use the same charge for all trains that have not undergone a retrofitting independent of conditions. Consequently, this makes it difficult to determine if the charge is equivalent to the cost of noise.

Overall, there are many measures that could reduce the cost of noise; however, it is difficult to determine to what extent these measures internalise the cost of noise since it depends on various factors such as number of individuals exposed and noise level.

4.4. INCLUDING NOISE COSTS IN ENERGY MODULE IN UCM2.0

The noise cost calculations in UCM2.0 are based on the marginal cost of noise presented in the European Commission’s handbook on the external costs of transport [8]. The marginal costs presented in Table 10 are averages for EU-28, i.e., including the United Kingdom. The calculation made in [10] can be carried out to reflect that EU member countries have different purchasing power adjusted GDP per capita. That is, marginal costs for each EU member state $i$ can be calculated using the following equation

$$MC_i = MC_{EU28} \left( \frac{GDP^{PPP}_{EU28}}{GDP^{PPP}_{EU28}} \right)^{\text{income elasticity}}$$

where the default income elasticity is 1 and $GDP^{PPP}_{EU28}$ is the average Purchasing Power Parity-adjusted GDP per capita for EU-28.
The innovations evaluated using UCM consider changes in noise levels, and not (necessarily) changes in vkm. The Roll2Rail project (that developed UCM [1]) therefore calculated the incremental cost per dB(A) based on the marginal cost per vkm and used the following expression:

\[(\text{pass-by train noise} - \text{TSI noise limit}) \times \text{incremental cost per dB(A)} + \text{marginal cost per vkm}.\]

The TSI (Technical Specifications for Interoperability) noise limit was set at 80 dB(A) for passenger trains and 84 dB(A) for freight trains.

UCM2.0 considers a similar approach as in [107] and use the updated marginal costs for noise in [8], including the option to let the PPP-adjusted GDP per capita influence the cost as described above. Furthermore, the default noise limits (targets)\(^2\) are changed in UCM2.0. Here it can be noted that WHO [56] recommends that railway noise should be reduced to 54 dB \(L_{DEN}\), and the recommended level for night-time is 44 dB \(L_{Night}\). Limit (target) values vary between countries, but most values are between 55 and 70 dB \(L_{DEN}\) [66]. These values are similar to the target levels specified in [105], which are 50, 60, and 70 dB(A) during the day for rural, suburban, and urban areas, respectively, and 10 dB(A) lower during night-time. These are the default values in UCM2.0.

The marginal cost per vkm and the incremental cost per dB(A) are different for each category in Table 10. In UCM2.0, the user can indicate a share of traffic with a certain traffic type (dense/thin) and time of day (day/night), as well as share of line within a certain area type (metropolitan/urban/rural).

\(^2\) In Error! Reference source not found. it is noted that the term ‘limit level’ can be interpreted as a maximum level that is not allowed to be exceeded. The term ‘target level’ is therefore used in UCM2.0.
5. UCM2.0 Vehicle Maintenance Module

The activities described in this section correspond to Task 1.4

5.1. THE VEHICLE MAINTENANCE MODULE IN UCM2.0

This section describes the proposal for the Vehicle Maintenance Module in the UCM2.0. The development of the UCM2.0 beta version was carried out in parallel to these work packages, so the figures and structure are preliminarily defined. The final UCM2.0 tool will be structured in this way, but changes might arise throughout the review and testing process that modify one or more traits of the module. These modifications will be described in the final deliverable D1.3.

5.1.1. Changes in the Vehicle Maintenance module in UCM2.0

The module shares the same structure with other modules of the UCM2.0:

- On top of the page the total vehicle maintenance costs, this is the final result in €/year. As shown below there are three values. As explained in the UCM2.0 manual, the tool always uses reference values that come from the System Platform Demonstrators definition (SPD1 High Speed, SPD2 Regional Trains, SPD3 Metro vehicles), the columns in grey. The result in the grey cell (SPD) comes from the reference calculation carried out, the orange and yellow cells correspond to two different cases (Case 1 and Case 2) that the user is analyzing.

![Vehicle Maintenance Module Screen Capture](1)

**Figure 16. The UCM2.0 Vehicle Maintenance Module screen capture (1)**

- Then the performance inputs. These are the specific inputs that the module requires from previous calculations carried out by the user or existing data from experience. In this case:
  - Wheelset reprofiling mileage (km)
  - Wheelset reprofiling depth (mm)
  - Probability of unavailability per vehicle per year

**Performance Inputs**

Cost due to different types of Vehicle Damage is calculated based on the following Performance Inputs:

<table>
<thead>
<tr>
<th>Performance Input Description</th>
<th>PI</th>
<th>SPD</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheelset reprofiling mileage (km)</td>
<td>WRM</td>
<td>150,000,00</td>
<td>25,000</td>
<td>100,000,00</td>
</tr>
<tr>
<td>Wheelset reprofiling depth (mm)</td>
<td>WRd</td>
<td>15,00</td>
<td>25,00</td>
<td>0,000001</td>
</tr>
<tr>
<td>Probability of unavail. per vehicle per year (-)</td>
<td>PI1</td>
<td>0,000010</td>
<td>0,00001</td>
<td>0,000001</td>
</tr>
</tbody>
</table>

**Figure 17. The UCM2.0 Vehicle Maintenance Module screen capture (2)**

- The Cost calculations provide a short explanation on how the calculations are carried out and provides is able to include the costs of unavailability.
Cost calculation

The module calculates the costs of Wheel Maintenance based on the number of reprofilings, depth of each reprofiling, and reprofiling costs. It considers how many times the wheel can be reprofilled before needing a wheel replacement. It is simplified so that decimal values are used.

For a full description of the calculation procedure refer to the User Manual.

\[
CW = CW_{repr} \left( N_{repr} - \text{floor} \left( N_{repr} \right) \right) + CW_{repr} N_{repr} \quad \text{(V.1)}
\]

repofiling when wheels are replaced does not count

\[
N_{repr} = \frac{D_y}{WRM} \quad \text{(V.2)}
\]

\[
N_{repr} = \frac{N_{repr} \text{ with } \frac{d}{d_{max}}}{\text{max}} \quad \text{(V.3)}
\]

The module calculates the costs of unavailability based on the estimated probability for unavailability per year per vehicle. For a full description of the calculation procedure refer to the User Manual.

\[
C_Q = \frac{P}{11} \cdot Q_1 \cdot N_v \quad \text{(V.4)}
\]

5.1.2. The inputs of the Vehicle Maintenance module in UCM2.0

The Calculation inputs first part includes the global inputs, they are called “global” as they are used by other modules and consequently directly defined in the landing page (first page) of the tool. The user cannot modify the grey cells, but can change the values of the cells in Case 1 and Case 2. The SPD is kept as a reference to which the cases are compared.

Intermediate variables

These are intermediate calculations that are interesting to highlight from a cost calculation perspective.

<table>
<thead>
<tr>
<th>Intermediate variables</th>
<th>I</th>
<th>SPD</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of reprofilings per year</td>
<td>N_{repr}</td>
<td>3,00</td>
<td>3,00</td>
<td>4,50</td>
</tr>
<tr>
<td>Number of replacements per year</td>
<td>N_{repl}</td>
<td>0,56</td>
<td>0,94</td>
<td>0,84</td>
</tr>
<tr>
<td>Wheelset maintenance costs per year (€)</td>
<td>CWM</td>
<td>3,000,00</td>
<td>3,000,00</td>
<td>4,000,00</td>
</tr>
<tr>
<td>Unavailability costs per year (€)</td>
<td>CVU</td>
<td>5,00</td>
<td>5,00</td>
<td>0,50</td>
</tr>
</tbody>
</table>

5.1.2. The inputs of the Vehicle Maintenance module in UCM2.0

The Calculation inputs first part includes the global inputs, they are called “global” as they are used by other modules and consequently directly defined in the landing page (first page) of the tool. The user cannot modify the grey cells, but can change the values of the cells in Case 1 and Case 2. The SPD is kept as a reference to which the cases are compared.

Calculation Inputs

The following inputs are are used for the calculation of the Module costs.

Global Inputs

These are defined in the Case Selection page and cannot be modified here as they affect different Modules.
The Calculation options second part includes the Module inputs, they are specific to this vehicle maintenance module. Again, the user cannot modify the grey cells, but can change the values of the cells in Case 1 and Case 2. The SPD is kept as a reference to which the cases are compared.

<table>
<thead>
<tr>
<th>Module inputs</th>
<th>I</th>
<th>SPD</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs for one reprofilling operation, both wheels (€)</td>
<td>CWrepr</td>
<td>1,000,00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Costs for the replacement of two wheels in a wheelset (€)</td>
<td>CWrepl</td>
<td>2,000,00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. radius reduction (mm)</td>
<td>dR_max</td>
<td>80,00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual cost of unavail. per vehicle - penalty (€)</td>
<td>CU_pen</td>
<td>100,000,00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 21. The UCM2.0 Vehicle Maintenance Module screen capture (6)

5.1.3. The maintenance options

The default maintenance pattern is to reprofile the whole wheelset when one of the maintenance limits is reached. As additional options, the possibility of increasing the reprofiling frequency is considered. In that case, this should be directly added to the PIs as input. If the variable frequencies affect the maintenance costs per unit, these should also be modified in the respective Case.

5.2. WEAR AND ROLLING CONTACT FATIGUE

From the UCM2.0 perspective, the conceptual way of simulating wear and RCF does not change from the UCM1.0 framework. A set of MBS simulations are carried out with pre-defined constraints and operational conditions, and the outputs of these are used as an input for a wear calculation model. The results are then used for updating the wheel or rail profiles, which loop back to the MBS simulations, now carried out with slightly worn profiles. This loop is performed until a certain condition is reached (limits in mileage, MGT, crack depth, profile wear measures). There was one main issue that needed to be addressed: the definition of a single way for calculating all the damage in wheels and rails, simplified for enabling differential damage calculations in a fast and robust way.

5.2.1. Wear and RCF simulation in the UCM framework

The variety of procedures for wear and rolling contact fatigue (RCF) calculation in the ROLL2RAIL UCM [1] gave a variety of results due to the calibration of individual techniques, but a unified simplified proposal was proposed in an appendix [108]. This proposal has been evaluated with regards to simplicity and accuracy loss, targeting not the absolute but the differential wear and RCF as variables.

Additionally, as from a practical perspective, both wear and RCF are considered at the same time in the simulation, it is therefore feasible to reduce all the wear and RCF KPIs defined in ROLL2RAIL to a single unified KPI, e.g. “reprofiling depth”, creating a much simpler interface between the simulation modules and the UCM.
5.2.1.1. Background
The current work is to study on the idea which implies that the wear rate is more or less constant during, or at least in a certain period, of a wheel life. To investigate this matter, at the first stage of the study, a test run has been conducted using a rigid body dynamic model of an electric multiple unit passenger train (EMU). To calculate wear, iterative simulations have been performed where in each iteration an Archard based wear calculation methodology is applied. Moreover, the calculated worn profile is updated at the end of iteration and used as inputs for the upcoming iteration. Iterative simulations have been performed until 200,000 km of simulated running distance achieved.

In the next stage of the study, the evolution of the wheel profile characteristics i.e. flange height and flange thickness as well as the worn area have been analysed. Furthermore, the calculated wear depth from distinct iteration steps, corresponding to different simulated running distance, have been linearly extrapolated to estimate the shape of the evolved wheel profiles. Finally, the wheel characteristics which are calculated via extrapolation are compared with the ones from the iterative simulations and the results are discussed. In the coming sections the details of the simulation setups, wear calculation methodology and post processing of the results are reviewed.

5.2.1.2. Wear modelling
The core of Archard’s wear theory [109] is that for adhesive wear, the depth of removed material (W) per sliding distance (S) is proportional (with a proportionality factor k) to the quotient of the pressure (P) and the hardness (H) of the softer material.

\[ W = k \frac{P \cdot S}{H} \]

The wear calculation methodology starts with collecting the inputs of time domain dynamic simulation. These data should reflect the actual rail network. After performing the simulations, the wheel-rail contact responses like creepages, contact size etc. are collected in each wheel turn and the corresponding wear depth is calculated in the contact patch according to the previous equation. Furthermore, the calculated wear depth should be summed and integrated along the direction of the train speed. After a certain travelled distance, the collective wear depth should be applied on the wheel profiles and updated new simulations will be launched. These cycles are called ‘wear-steps’ and they continue to repeat until the desired travelled distance is obtained, see Figure 22.
It should be noted that wear is assumed to be uniformly distributed around the wheel and its symmetric, i.e. the same on both left and right wheels.

5.2.1.3. Wear map
The proportionality factor, $k$, of the wear depth formula, plays a key role in the calculation process. In [110], the authors simplified the results of series of field tests and laboratory experiments which were performed by Olofsson and Telliskivi [111] and created a wear map. Since then, this simplified map has been used in several research works. The map comprises of four regimes that are functions of sliding velocity and normal pressure in the contact patch. However, the transitions of the wear regimes and the corresponding $k$ values should be calibrated within a certain suggested range. In this work, the coefficients of the wear map are calibrated in such that the evolution of the flange height gets the same trend as the research conducted in [112] with a same wheel profile and similar operational conditions. The original and tuned parameter are presented in Table 11.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Original value</th>
<th>Tuned value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_1$</td>
<td>350e-4</td>
<td>35e-4/5</td>
</tr>
<tr>
<td>$K_2$</td>
<td>5e-4</td>
<td>5e-4/5</td>
</tr>
<tr>
<td>$K_3$</td>
<td>35e-4</td>
<td>35e-4/5</td>
</tr>
<tr>
<td>$K_4$</td>
<td>5e-4</td>
<td>5e-4/5</td>
</tr>
</tbody>
</table>

5.2.1.4. Simulation setups
The simulation model has been built in MBS software GENSYS [128] and the results has been validated against measurement. The model has been used in several academic and industrial projects; however, due to confidentiality agreements the model and any information of the vehicle cannot be discussed in this work.
5.2.1.5. Track sections

Eleven distinct track sections have been used in this study. Each track section has a specific geometry i.e. radius, cant etc. The geometry and the corresponding irregularities of the track sections are chosen from measured track data from the west coast of Sweden. The curve radii intervals are presented in Table 12.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average cant [mrad]</td>
<td>0.046</td>
<td>0.065</td>
<td>0.065</td>
<td>0.011</td>
<td>0.041</td>
<td>0.009</td>
<td>0.047</td>
<td>0.046</td>
<td>0.031</td>
<td>0.023</td>
<td>0.001</td>
</tr>
<tr>
<td>Average Gauge [mm]</td>
<td>1456</td>
<td>1443</td>
<td>1442</td>
<td>1444</td>
<td>1438</td>
<td>1439</td>
<td>1437</td>
<td>1439</td>
<td>1444</td>
<td>1438</td>
<td>1436</td>
</tr>
</tbody>
</table>

5.2.1.6. Rail profiles

Depending on the curve radii intervals the rail profiles are chosen between four distinct types, ranging from nominal profile to the most worn shape. These rail profiles are measured and believed to can fairly represent the Swedish rail system. Note that the rail inclination in Sweden is 1:30.

5.2.1.7. Wheel-rail friction coefficient

The static wheel-rail friction is a function of material in contacts and the environmental conditions such as humidity and temperature. Thus, its value in a certain section of a track may change during a day. To simulate such a behaviour, friction values are chosen randomly with normal distribution around 0.35 and standard deviation of 0.1 for each iteration. This friction is called the iteration friction and is to simulate the changes of friction in at most 2000km of running distance. However, within each iteration and for each of the 11 track sections the values of friction are chosen with the probability distribution around the iteration friction value and standard deviation of 0.05 to simulate the changes of the friction coefficient in shorter period. Using this technic distributes the contact location (and thus corresponding wear) over the wheel and rail profiles and thus a wheel profile wears smoothly leading to less mathematical smoothing of the profile. The histograms of all these friction values after around 440 iterations i.e. around 200,000km of simulated running distance are shown in Figure 24.

Figure 23. rail profiles used in the simulations; left: high rail & right: low rail
Figure 24. Histograms of wheel-rail friction coefficients in all the simulated track sections after 200,000 km of simulated running distance.
5.2.1.8. Vehicle speed

The initial speed of the vehicle is calculated separately in each track section and each iteration to create maximum 150 mm of cant deficiency. However, the maximum speed is set to 180 km/h.

![Histograms of initial vehicle speed in all the simulated track sections after 200,000 km](image)

**Figure 25.** Histograms of initial vehicle speed in all the simulated track sections after 200,000 km of simulated running distance

5.2.1.9. Results and discussion

After over 420 iterations the simulated running distance reached around 200,000 km. This is since that the maximum running distance in each iteration is limited to 2000 km while the maximum wear depth is set to 0.25mm. Thus, exceeding the limit value in wear reduces the running distance proportionally. The calculated worn shaped of the S1002 profile is shown in Figure 26.

![Nominal S1002 profile and simulated worn profile](image)

**Figure 26.** Nominal S1002 profile and simulated worn profile after 200,000 km

The evolution of the flange height and flange thickness are presented in Figure 27. As it is seen in the figure, flange height is evolving quite linearly; however, situation for flange thickness is...
somewhat more complicated. This is since that flange thickness is a function of flange height and its evolution may not be linear, and it is extremely depending on the curve radii distribution of the line.

![Simulated flange height and flange thickness evolution after 200,000 km of simulated running distance](image1)

**Figure 27.** Simulated flange height and flange thickness evolution after 200,000 km of simulated running distance

However, the results of this study show that the worn area is growing linearly. This implies that with few iterations one can extrapolate the area of removed material due to wear and estimate its value in longer simulated distance, i.e. Figure 28.

![Simulated worn area as a function of running distance](image2)

**Figure 28.** Simulated worn area as a function of running distance

Moreover, assuming the idea of linear evolution of the worn area, the calculated wear depth is tried to be extrapolated in several distinct iterations. In other words, the calculated wear depth over the wheel profile is extrapolated using the rate of the worn area. Furthermore, this extrapolated wear depth is subtracted from the initial wheel profile so that an extrapolated worn profile can be achieved. Finally, the wheel characteristics i.e. flange height and thickness are recalculated for this
extrapolated wheel profiles and the results are compared with the simulated flange height and thickness i.e. Figure 27. The results of this section are summarised in Figure 29. As it is seen in the figure the extrapolated wheel characteristics are not well matching the ones from the iterative simulations especially at the beginning of the simulations. However, at the end of simulations where, the profile obtains a more stable shape the deviations of the extrapolated characteristics.

**Figure 29. Comparison between extrapolated and simulated evolution of flange height and flange thickness.**

The conclusion is that there is no possibility for simplifying the simulation models in the form proposed in R2R, due to the lack of consistency between different sampling frequencies. The wear and RCF simulations will need to be carried out in a loop.

For this non-simplified calculation (more complex and time consuming) to be sued by different stakeholders, a software package that enables the simulation of the PIs from MBS simulation results is proposed. This way the MBS simulations are the only thing that stakeholders need to perform and, considering the Manchester Benchmarks[129], it can be assumed that the results of the wheel-rail contact forces and creepages are robust across different simulation techniques and individual stakeholders.

### 5.2.2. Wear and RCF in UCM2.0

The proposal for the UCM2.0 is the following:
- Uniform wear is simulated with Archard [109]. RCF is simulated with Dirks’ model [130]. The selected models have demonstrated their capabilities in many previous works, but are still arbitrary choices based on the expertise of the partners. These are described in [1] and further references can also be found there.
- These modelling techniques are not simplified in any way. As shown in the previous subsection, simplification can easily lead to extreme differences in the final result for the PIs.

An advanced user of the UCM 2.0 framework will have to code the damage calculation loop (Figure 30), including a damage simulation package coupled to the MBS simulations.

![Diagram of simulation setup](image)

**Figure 30. Simulation setup for wheel or rail damage calculation.**

For wheel or rail damage calculation, a simulation package will be needed (in grey in Figure 30) that performs the calculation of the PIs from the MBS simulation results. The contact models and parameters for simulating uniform wear and fatigue will be strictly defined to ensure the consistency of the results in comparison to the ones reported in R2R. For ensuring the replicability of results, a simplified calibration case will be appended.

For **wheel damage** calculation, the simulation package needs to be able to calculate wheel profile evolution and RCF depth and location when inputted the MBS results for a certain set of simulations. The precise inputs etc. will be defined in the Simulation Guidelines, but a short description would be as follows:

- A specific set of curves should be simulated (MBS). The curves will be pre-defined in the form of *radius, length, cant, irregularities, speed and percentage of the line*. Track characteristics will also be fixed in the form of *MBS track model and track stiffness*.
- The simulation output is the simulated wheel profile, and wheel-rail contact variables needed for the calculation of the damage: creep force, creepage, contact position (for all the different contact points).
- The sim. Package will have defined the following variables: *normal contact model, tangential contact model, discretization, wear coefficients, RCF coefficients*. The output results should be in the form of *updated wheel profile and crack depth and position* in the wheel, and corresponding mileage.
- These results have to be further postprocessed as *material removal depth* according to a set of fixed reprofiling limits for uniform wear and crack depth.
This should be coded in a loop so that it is run until a certain *mileage* is reached, alt. a certain *material removal depth* is reached. These two output results are the PI for wheelset reprofiling costs.

For **rail damage** calculation, the simulation package needs to be able to calculate *rail profile evolution* and *RCF depth and location* when inputted the MBS results for a certain set of simulations. The precise inputs etc. will be defined in the Simulation Guidelines, but a short description would be as follows:

- A specific set of curves should be simulated (MBS). The curves will be pre-defined in the form of *radius, length, cant, irregularities, speed* and *percentage of the line*. Track characteristics will also be fixed in the form of *MBS track model* and *track stiffness*.
- The simulation output is the simulated *rail profile*, and wheel-rail contact variables needed for the calculation of the damage: *creep force, creepage, contact position* (for all the different contact points).
- The sim. Package will have pre-defined the following variables: *normal contact model, tangential contact model, discretization, wear coefficients, RCF coefficients*. The output results should be in the form of *updated rail profile* and *crack depth and position* in the rail, and corresponding *MGT*.
- These results have to be further postprocessed as *material removal depth* according to a set of fixed *grinding limits* for uniform wear and crack depth.
- This should be coded in a loop so that it is run until a certain *MGT* is reached, alt. a certain *material removal depth* is reached. These PIs for rail grinding costs are these values for *curved track* and for *straight track*.

The precise parameters for these simulations will be defined and calibrated throughout the simulations of the Study Cases in Task 1.6.

### 5.3. **CONDITION BASED MAINTENANCE (CBM)**

#### 5.3.1. **Objective and context**

This section covers a search for existing CBM systems, a legal context as some of these systems are mandatory in some cases and optional in others, and the opinion of a metro operator (MdM) regarding these systems at present and future plans. The final aim of this work is to be able to analyse CBM systems in the UCM 2.0.

The service life and the maintenance intervals of components depend, beneath other factors, on the operating conditions, which are often difficult to predict. In order to ensure operational safety and other requirements like e.g. comfort, the maintenance intervals for certain components are set relatively low. In some cases, such fixed maintenance intervals may lead to unnecessary maintenance action, i.e. maintaining or replacing a component, which is still well within its limits.
An alternative, which has a potential to reduce such unnecessary maintenance action, is condition based maintenance (CBM). Here, the state of the relevant component is continuously monitored by sensors, which measure e.g. vibrations or temperature. Thereby, degradations or developing errors can be detected so that the component is only replaced when necessary. This could potentially save unnecessary maintenance efforts, contribute to the operational safety of the entire system, and generate less material waste due to the optimised life lengths of the components.

There are already several mature applications of CBM in railway vehicles for components like wheels, wheelset bearings, gearboxes, traction motors, transmission, and the suspension. However, it might not always immediately be clear for the user, for which components CBM and monitoring provide a better cost efficiency. In this context, the costs for the monitoring system including its purchase, installation and operation are relevant, too. Their appropriate description requires the definition of the relevant cost parameters and the determination of their values.

Regarding vehicle maintenance, the module UCM was focused just on the wheel; this shall be extended to maintenance of other running gear components, including CBM as a valid KPI generator. The aim was to explore how the UCM would be capable of evaluating and comparing LCC of various maintenance strategies including different individual configurations of monitoring systems (subtask 1.6.2 case studies). This requires the formulation of the inputs required from the user including field experience and data from the CBM system supplier. Overall, the aim is to help the user to determine whether the installation of a health monitoring system pays off, and how such a condition-based monitoring system should be configured in order to ensure its benefit.

5.3.2. Legal context

It has to be noted that certain monitoring systems for railway systems are already subject to legal regulations; in certain cases, such systems are mandatory. What follows is based on the document from Commission Regulation (EU) concerning a technical specification for interoperability relating to the rolling stock — locomotives and passenger rolling stock subsystem of the rail system in the European Union [113]. Some parts relevant for CBM:

- 4.2.3.3.2.1. Requirements applicable to on board detection equipment

  (2) The bearing condition shall be evaluated either by monitoring its temperature, or its dynamic frequencies or some other suitable bearing condition characteristic.
(3) The detection system shall be located entirely on board the unit, and diagnosis messages shall be made available on board.

- 4.2.3.4.2. Running dynamic behaviour

(c) Additional requirements when an instability detection system is installed (option)
(7) The instability detection system shall provide information regarding the need to take operative measures (such as reduction of speed etc.), and it shall be described in the technical documentation. The operative measures shall be described in the operating documentation set out in clause 4.2.12.4 of this TSI.

- 4.2.4.6. Wheel-rail adhesion profile — Wheel slide protection system
- 4.2.4.6.2. Wheel slide protection system

(8) Wheel rotation monitoring system (WRM):
Units of design maximum speed higher or equal to 250 km/h shall be equipped with a wheel rotation monitoring system to advise the driver that an axle has seized; the wheel rotation monitoring system shall be designed according to the specification referenced in Appendix J-1, index 30, clause 4.2.4.3.

The SKF Railway technical handbook, Volume 1 [114] also refers to the TSI. In the chapter “Wheelset monitoring” it mentions the following requirements and function enhancements:

- **TSI requirements**
  - Hotbox detection, detection parameters:
    - Axlebox temperature measurement on each axlebox
  - Bogie hunting detection, detection parameters:
    - Acceleration measurement in accordance with UIC 515-1

- **TSI function enhancement**:
  - Derailment detection, detection parameters:
    - Acceleration measurement on each axlebox, algorithm to be defined

5.3.3. Possibilities – what can be monitored and how can it be monitored?

A search has been conducted and in what follows examples of the systems found are indicated. In [115] a list of subsystems and detection parameters are presented:

- Wheel, detection parameters:
  - Wheel profile/out of roundness
- Axlebox bearing(s), detection parameters:
  - Temperature
  - Relative temperature in comparison to other axlebox bearings
  - Early bearing damage
  - Vibration levels
- Gearbox (transmission), detection parameters:
  - Bearing temperature
  - Early bearing damage
o Unbalance
o Misalignment
o Shaft deflection
o Loose parts
o Vibration levels
o Damaged gear wheel
o Resonances
- Gearbox oil, detection parameters:
  o Oil temperature
  o Oil level
- Traction motor, detection parameters:
  o Bearing temperature
  o Early bearing damage
  o Vibration levels
- Cardan shaft, detection parameters:
  o Unbalance
  o Damaged coupling

Temperature and vibration sensors are the more frequently used but there are other options to enhance the monitoring system specially some critical systems such as the gearbox [119]

5.3.4. Systems available and implementation cases

Only some examples are cited here. One that is well documented is the Knorr-Bremse “COMORAN” (“COndition MOnitoring for RAilway ApplicatIoNs”) [116][117][118]. Reference [117] explains how the system combines the safety-relevant monitoring of bogies with condition monitoring. The combination of these two functions provides the input for performing condition-based maintenance of bogie components, which ensures that trains are only taken into maintenance depots when components are generally in need of maintenance. Its main features:

- Equipment
  o Multifunctional sensor FS04, installed at the axle boxes
  o Electronic device (monitoring board) RB06
- Measurement of velocity, temperature and acceleration
- Safety-critical monitoring functions (TSI high speed)
  o Hot axle boxes detection (temperature)
  o Detection of non-rotating axles (velocity)
  o Derailment detection (acceleration)
  o Bogie hunting (acceleration)
- Non-safety relevant monitoring
  o Wheelset bearing
  o Wheel flats
  o Wheelset guidance
  o Track monitoring

SKF in references [114][115] proposes:
- Axletronic
  - Axle box sensors measuring vibration, temperature, speed and direction of rotation
  - Installation in new vehicles and subsequent installation in existing vehicles possible
- IMx-R
  - Electronic device connected to the Axletronic sensors; evaluation of the signals received from the sensors

5.3.5. Metro operators background and vision on CBM

5.3.5.1. Metro de Madrid

The importance for CBM applications is based on the safety and cost estimations considered by MdM, but these figures may differ for other railway operators, especially for mainline or high-speed railways whose trains have different operating conditions.

Currently, some CBM systems are in operation, but their maturity is not the same in all of them. For example, there is a detector of faults in gearboxes which is patented by MDM. It does not transmit any data to the wayside yet, but the on-board equipment has been successfully tested in the last years. On the other hand, there is a device to retrieve the temperatures in the gearboxes which works only in the TCN domain. We provide these two examples in order to give some context about our future needs which are conditioned by our current systems.

Regarding the part of the problem, which is not related to the rolling stock, MsM is now working on a large project which is focused on the digital transformation of the maintenance of the rolling stock, as well as an upgrade of the data centres and train-to-wayside communications.

Regarding MdM needs, they acknowledge that some CBM applications are not more than an idea but many others are mature enough to be installed now. The following list does not take this into account, but only includes use cases related to running gear (therefore, neither pantograph-catenary contact monitoring nor pneumatics are included, among others):

1. Wheel profile parameters: let the operator know the real wheel profile in order to schedule the optimal time for reprofiling.
2. Wheel damage: early detection of wheel damage & defects in order to increase the quality of service.
3. Lubrication: this one is complementary to the ‘wheel damage’. The idea is to measure flange lubrication in order to avoid issues and also to prevent thin wheel flanges.
4. Temperature in bearings: this one suits better for HST but, given that, the time between normal-operation and a critical breakdown could be very short, we find this use case interesting.
5. Vibrations in bearings: same as #4
6. Vibration in gearboxes: this one would let the maintenance people to know in advance the time needed for each bogie in the overhauls. Now, this vibration analysis is done manually
when the train is in the workshop, with very little advance in order to schedule human resources.

7. Comfort & stability sensorisation: due to the implications it is reasonable to have a set of trains equipped with sensors (i.e. accelerometers). By having some of these trains circulating on each line, undesired effects like hunting (among others) can be detected and reported as soon as they occur.

The architecture beyond the monitoring system is typical:
- Acquisition hardware
- A gateway (to onboard networks and wayside networks) with both processing and storage functionalities

5.3.5.2. MTR, Hong Kong
Reference [120] presents the railway applications of Condition Based Monitoring (CBM) developed and implemented in the metro system of Hong Kong since 1989. In this paper, the limitations of traditional preventive and reactive maintenance approach in railway operations environment will be explained. CBM has been a proven technology to effectively enhance the RAMS performance of equipment and optimise the maintenance resources, thus reducing the overall life cycle cost. Shows a condensed overview of the subsystems developed

<table>
<thead>
<tr>
<th>CBM techniques</th>
<th>Equipment used</th>
<th>Key applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration Analysis</td>
<td>Transducer, spectrum analyser</td>
<td>Fan, AHU (<em>air handling unit, i.e. blower, heating and cooling elements etc.</em>), Chiller, Escalator, Pump</td>
</tr>
<tr>
<td>Tribology / Oil Analysis</td>
<td>Oil analyser</td>
<td>Chiller, Escalator, Transformer</td>
</tr>
<tr>
<td>Thermo-analysis</td>
<td>Infra-red images</td>
<td>ACB (<em>air circuit breaker</em>?), Transformer, Switchboard</td>
</tr>
<tr>
<td>Ultrasonic Detection</td>
<td>Ultrasonic Leakage Detector</td>
<td>ACB, Transformer, Switchboard</td>
</tr>
<tr>
<td>Machinery Balancing</td>
<td>Photo cell, laser beam, etc</td>
<td>Fan, AHU (<em>air handling unit</em>), Pump</td>
</tr>
<tr>
<td>Ultrasonic detection</td>
<td>Ultrasonic Testing Vehicle</td>
<td>Rail</td>
</tr>
<tr>
<td>Optical / laser imaging</td>
<td>Track / Overhead Line</td>
<td>Vehicle Contact wires and rail</td>
</tr>
<tr>
<td></td>
<td>Geometry</td>
<td></td>
</tr>
<tr>
<td>Ultrasonic detection</td>
<td>Hand-held for axle crack</td>
<td>Axle</td>
</tr>
<tr>
<td>Mechanical measurement</td>
<td>Hand-held (MiniProf)</td>
<td>Wheel</td>
</tr>
</tbody>
</table>
5.3.6. CBM systems in UCM2.0

There is no specific module for CBM systems in UCM2.0, The Vehicle Maintenance Module concentrates in wheel maintenance, however in Task 1.6.2 there are two case studies foreseen regarding CBM systems and how the advantage of having them on-board could be quantified.

In most cases fixed maintenance intervals for components, e.g. dampers, are set. These intervals are based on estimated life of the components and do not consider the actual current state of the component. The consequence is that components which are still functioning well are replaced (and thrown away), over-maintaining is very expensive.

Regarding the implementation of a CBM system the following questions have to be answered:

a) which components can/should be monitored? Examples: Bearings, gear boxes, …
b) how can the components be monitored? Examples: Temperature sensors, accelerometers, etc..
c) What are the relevant costs? Purchase, installation, staff training, operation, etc.
d) What are the savings?
e) What are possible risks? Example: False alarms, sensor failure.
f) “360° view” necessary: focus on technology, costs and processes is needed

The final goal would be to find out if a different maintenance strategy pays off. There are some data that are required in order to compared the costs of two different maintenance strategies the following costs have to be taken into account:

1. Analysis of the costs for maintenance of a specific component:
   a) Refurbishment costs, \( C_{\text{ref}} \)
   b) Replacement costs \( C_{\text{rep}} \)
   c) Costs of one life cycle: \( C_{\text{LCC}} = n_{\text{ref}} \cdot C_{\text{ref}} + C_{\text{rep}} \)

   Where \( C_{\text{LCC}} \) refers to the cost for the expected lifetime of the component in which \( n_{\text{ref}} \) refurbishments were carried out. In case the component cannot be refurbished, just be simply replaced, then \( n_{\text{ref}} \) is set to zero. The costs for replacement include all the costs, also unavailability costs.

2. Analysis of the costs for maintenance of a specific CBM system:
   a) Fixed costs, \( C_{\text{fix}} \), i.e. purchase, training of operations staff
   b) Operational costs \( C_{\text{op}} \), i.e. system supervision and maintenance
   c) Costs of one life cycle: \( C_{\text{CBM}} = C_{\text{fix}} + C_{\text{op}} \)

   Additionally, there is a need to relate the expected lifetime of the CBM system with the lifetime of the component itself in order to calculate the maintenance cost of the component. And finally this cost has to be related with the distance run by the vehicle per year, as the UCM2.0 calculates cost on a yearly base.
Using this procedure, the cost of two maintenance strategies can be compared, this will be carried out in task 1.6.2 using a case study.

5.4. WHEEL MAINTENANCE

Figure 31 illustrates very well a typical material loss by the wheel due to wear in service and due to the reprofiling when the original profile is reproduced.

Figure 31. Typical new and service worn profiles together with the new profile after turning and the radius loss

Figure 32 shows the wear evolution of a S1002 profile measured at different mileages [121]. This reference [121] presents results of the wheel profile wear according to the Archard wear law, where the computational model of railway vehicle was riding on a track at a constant velocity. The vehicle was moving along track where the rail profile was defined by a standard (UIC 60 profile), with a cant of 1:40, or on the track profile measured directly on the track - the S 91700_16 profile with the cant of 1:20. The simulations were created with use of the SIMPACK software.
Figure 32. Wear evolution of a S1002 profile over mileage [121]
The radius loss is illustrated in

![Graph of wear depth of a S1002 profile over mileage](image)

**Figure 33. Wear depth of a S1002 profile over mileage [121]**

The \( \Delta r \) -definition of radius loss: difference to be removed in order to refurbish the wheel - is non-linear; it is generically represented over a mileage in Figure 34. Radius loss \( \Delta r(s) \) depending on the mileage \( s \);

![Graph of radius loss \( \Delta r(s) \) depending on the mileage \( s \)](image)

**Figure 34. Radius loss \( \Delta r(s) \) depending on the mileage \( s \)**

The cost of different strategies are based on the following data and sequence

- Technical data
  - Radius loss \( \Delta r(s) \) depending on the mileage \( s \); definition of radius loss: Difference to be removed in order to refurbish the wheel
Admissible radius loss $\Delta r_{\text{max}} = r_0 - r_{\text{min}}$; definition: Difference between the original radius $r_0$ and the minimum admissible radius $r_{\text{min}}$

- Costs
  - Total costs for one wheel reprofiling including labour costs, unavailability costs etc., $C_{\text{repr}}$
  - Total costs for wheel replacement including material costs, labour costs, idle costs etc, $C_{\text{repl}}$

- Calculation
  - Select a mileage $s_{\text{ref}}$ for one refurbishment cycle and determine the corresponding radius loss $\Delta r(s_{\text{ref}})$
  - Determine the number of reprofiling cycles: $n_{\text{rep}} \leq \Delta r_{\text{max}}/\Delta r(s_{\text{ref}})$
  - Calculate the total costs of one life cycle: $C_{\text{LCC}} = n_{\text{rep}} \cdot C_{\text{repl}} + C_{\text{repr}}$

And the process is illustrated in Figure 35

**Damage evolution**
- Abrasive wear
- Subsurface cracks
- ...

**Maintenance threshold**, e.g.
- Wear depth in one vehicle
- Difference of radii at one wheelset
- Equivalent conicity
- Fatigue cracklength

**Cost preprocessing**
- Working costs
- Material costs
- Unavailability costs
- ...

**Calculation of maintenance cycles**
- $s_{\text{ref}}$
- $\Delta r_{\text{max}} = r_0 - r_{\text{min}}$

**LCC calculation**
- $n_{\text{ref}}$
- $C_{\text{LCC}}$

Figure 35. Schematic representation of different wheel maintenance strategies

This analysis will be carried out as part of Task 1.6.2 using the UCM2.0 tool
6. Conclusion

The deliverable has fulfilled its objective which was to describe the upgraded UCM2.0 capabilities regarding Energy and Noise calculations and cost valuations (Task 1.3) and Vehicle damage and maintenance modelling (Task 1.4).

The deliverable has devoted an extensive discussion on CO₂ emissions, methods to monetise the cost of CO₂ emissions and examples of calculations of CO₂ emissions and costs in rail transport. These costs are now included has part of the Energy Module of UCM2.0. The Energy module of UCM2.0 has been simplified without losing accuracy. The fact that all the modules share the same structure will surely help the user and spread the use of this tool which at the end is intended to boost innovations in the rail sector.

Extensive work has been carried out to describe the fundamentals of noise costs and the scientific basis of the Noise Module in the UCM2.0. The noise costs are updated in UCM2.0, and the new module also includes the possibility to choose the existing traffic volume (dense/thin), time of day, and persons exposed (via area type) – aspects that will have an impact on the extra noise cost of the innovation considered.

The vehicle maintenance vehicle, which main part is the wheel maintenance has also been reworked. It now has a structure which is user friendly.

Overall, the UCM2.0 has required two parallel paths.
- Fill the gaps in the methodology, incorporating economic and engineering approaches
- Ensure the balance between simplicity and accuracy.

Now that these three modules are ready and giving the fact that the work on the module regarding infrastructure is also available, the tool can face the case studies foreseen in Task 1.6.2 which will provide an excellent test platform for UCM2.0. These case studies cover: New traction components, Brakes, Hybrid Carbody, Hybrid wheelset, Bogie innovations (active steering and low weight materials), wheel repprofiling strategies, CBM systems.
7. References

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