rev2021 | Resource Efficient Vehicles Conference
14 – 16 June 2021

System-wide impact of vehicle innovations – Evaluating track-friendliness during vehicle design

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The cost of maintenance of railway tracks due to vehicle passage is a major limiting factor to the competitiveness of railway sector in EU. For instance, in Sweden in 2017 only, 2800 million SEK was spent on track maintenance and reinvestment due to wear and tear caused by traffic. Considering this, there is a major incentive to operate track-friendly vehicles that also facilitate economically feasible maintenance strategies. In this context, the NEXTGEAR project aims to incorporate a track-friendliness module in the 'Universal Cost Model 2.0' that can estimate operating costs for a given set of operational parameters such as vehicle suspension design, energy usage, track geometry, etc. Such a tool could be useful in estimating the costs for a train operator for a given route and application. However, estimation of costs due to track damage is a complex cross-disciplinary task encompassing varying domains such as vehicle dynamics, tribology, economics, maintenance policy etc so that actual damage in the infrastructure can be linked to maintenance actions and thus costs. Currently there are two major diametrical approaches such as the 'Bottom-up' Engineering approach that seeks to create accurate engineering models of vehicle, track, etc. Then there is the 'Top-down' Econometric approach that seeks to create statistical models linking the operating variables with historically recorded cost data. Also, track damage itself manifests in various forms such as wear RCF and settlement and it is extremely useful to understand the distribution of costs amongst them. Nowadays a Hybrid approach is being developed that can bridge the limitations of the other two methods. Eventually all these models seek to calculate differential operating costs due to the introduction of vehicle innovations during the design stage, hence contributing to the overall economic feasibility of the railway system.

1. Introduction

In the European Railway Sector, track owners and vehicle operators have been separated for the last decades, which decouples the different railway subsystems (infrastructure ownership, vehicle operation, maintenance for either of them, and rail vehicle manufacturing) so that there can be new players that compete for the commercial exploitation of these subsystems. The theoretical promise is that this allows for a better optimisation of the different subsystems. While technically true, there are still interactions between these actors, so the actions taken by one of them do affect the rest of the stakeholders.

In this context there are usually no issues regarding the daily operation of railway systems, where the individual optimisation of the subsystems can still be the optimal system case. However, vehicle innovations have almost completely disappeared due to the fact that the stakeholder that pays for the vehicles, the Vehicle Operator (VO), does not receive a significant economic benefit out of these innovations. There are certain benefits for the VO, such as reduced need for wheel maintenance, or lower energy consumption, but the economic savings that impact the vehicle directly are not enough for justifying a higher initial cost. However, if a system perspective is adopted, there are also benefits for the Infrastructure Manager (IM) as track damage is reduced, which might have a significant impact on the long-term savings for the whole railway system. A solution to try to overcome this limitation is to charge vehicle operators a variable Track Access fee that depends on how the specific vehicle influences track deterioration, but in the existing schemes the cost is calibrated against the marginal cost of track maintenance, so the operator would need existing experimental measurements and actual costs for the vehicles being studied. So an innovative running gear at a prototype stage (or lower TRL) cannot be used for the calibration of these models.

EU project Roll2Rail developed the so-called Universal Cost Model (UCM) that accounts for all aspects of running gear innovations that influence the whole railway system's Life Cycle Costs (LCC) [1]. The main objective is to create simulation-based framework and tools that will allow to compare a reference vehicle against an innovative one, showcasing the differential costs and benefits due to a certain innovation. It will increase the awareness of the impact of different bogie design concepts on different costs of the railway system, allowing Infrastructure Managers to assess different vehicle offers for a certain system, or the influence on an existing track of a novel vehicle concept, and even contribute to optimize 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.

2. Track-Friendliness

A key step towards calculation of life-cycle costs incurred at the wheel-rail interface is the assessment of track-friendliness of a wagon during its design stage. 'Track-friendliness' of a wagon/ bogie design is its propensity to cause minimal damage to track during its passing, which indirectly gives a measure of the expected costs incurred by the infrastructure manager in maintaining and replacing track components. Track damage itself manifests in different forms, each governed by a complex physical phenomena and requiring separate mitigating measures.

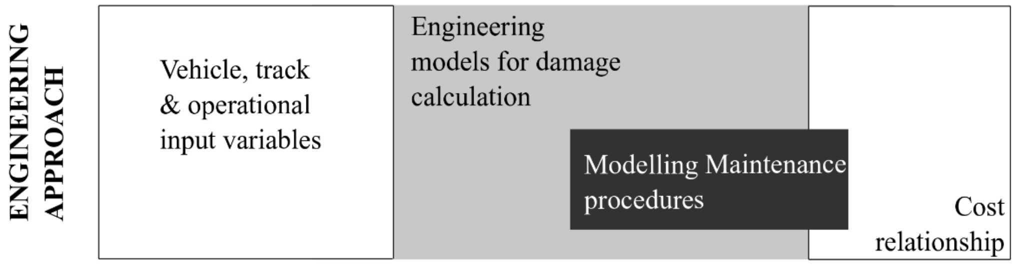
A lot of prior work exist to assess track-friendliness of freight wagons to help decide track access pricing strategies in the EU. These can be broadly classified into two approaches as explained by Smith et al. [2]:

- *Bottom-up approach:* They involve engineering simulation methods that estimate the track damage caused by the rail vehicles. Since the physical phenomena that cause damage is modelled step-wise and scaled up for a required running distance/ tonnage passage of wagons, it is regarded as 'Bottom-up'
- *Top-down approach* : These involve econometric methods that estimate a relationship between the actual maintenance costs obtained historically and the different attributes of traffic passing on the track using econometric methods. They do not explicitly consider the physical phenomena responsible for the creation and propagation of damage. They directly start from the final costs incurred to the infrastructure manager and therefore regarded as 'Top-down'.

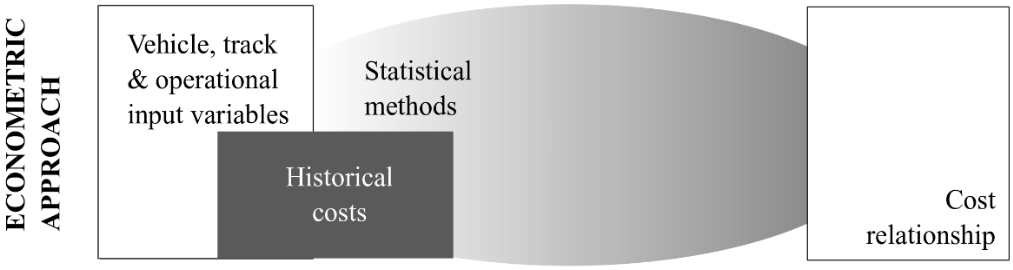
Both approaches carry some distinct advantages and address a part of the multi-disciplinary nature of track access pricing. There exist multiple methods in literature that come under each of the above approaches. Some of these methods are described in this section.

2.1 Engineering approach

Figure 1 illustrates a 'pure' engineering approach where detailed characteristics of vehicle, track operation (suspension design, track radii, wheel-rail contact friction levels, speeds, etc) are taken as inputs. Based on various running scenarios, the damage caused to track via various damage modes are calculated through Multi-Body-simulations (MBS) simulations. The outputs from simulations help quantify the damage. Öberg et al. [3] for instance identifies four modes of track damage and lists the damage quantification expression.



(a)



(b)

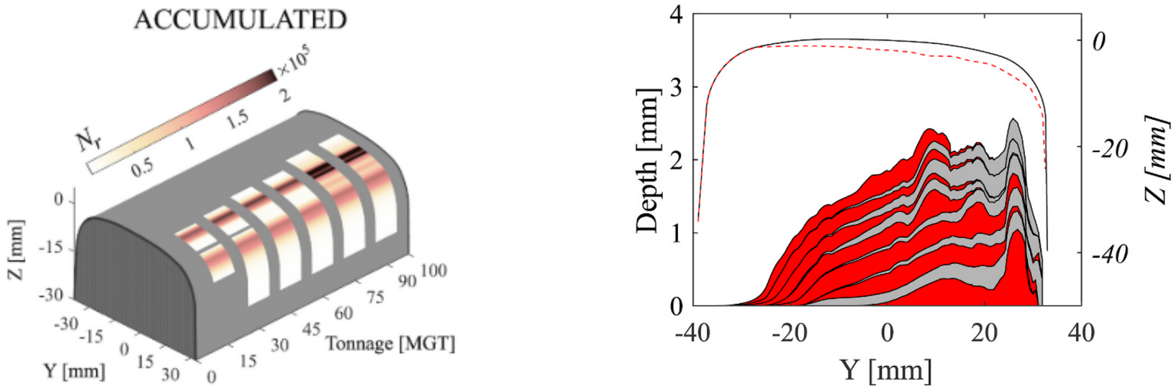
Figure 1. Different approaches to evaluate Track-friendliness to obtain a cost relationship between vehicle operational inputs and costs incurred by an infrastructure manager

They calculate the marginal cost for the passage of wagons as:

$$e_{ton-km,Z}(R_j) = \begin{cases} k_1 . {Q_{tot}}^3 \\ + k_2 \left[\sqrt{{Q_{tot}}^2 + {Y_{qst}}^2} \right]^3 \\ + k_{34} . \dfrac{\sum_{i=1}^{n_z} [f(T\gamma)_i]}{m_z} \end{cases} \quad (1)$$

Where Q_{tot} and Y_{qst} stand for vertical and lateral quasistatic wheel-rail forces respectively and $T\gamma$ stands for energy dissipated on the contact patch. The first term reflects the engineering output quantifying damage due to track settlement (${Q_{tot}}^3$), the second reflects the same due to track component fatigue ($[{Q_{tot}}^2+{Y_{qst}}^2]^{3/2}$) and the third reflecting the damage due to rail surface damage ($T\gamma$). Rail surface damage itself is further comprised of two damage modes namely wear and rolling contact fatigue, the effects combined in the form of a function f. Each term has a calibrated coefficient (k_1,k_2,k_{34}) forming a linear function between marginal costs and the engineering outputs. A similar approach was also adopted by [4] to compare track-friendliness of bogie designs. This approach of individually identifying the contribution of each track damage mode and calculation of the total costs was also adopted in the EU project Roll2Rail [5] that put forward one of the first UCMs in the area [1]. Similar track access pricing methods rooted in the engineering approach are also in use to a certain extent by infrastructure managers in the UK [6], Austria and Switzerland [7].

More advanced methods capable of predicting the evolution of rail geometry with increasing tonnage passage are also recently being developed. They take the engineering approach a step further from calculating dynamic forces such as the terms in equation (1) to predicting the shape of the rail profile after a large tonnage passing such as the work done by [8]. More recently, the impact of intermediate maintenance measures and the interaction between different modes of rail surface damage were also implemented in [9]. The main benefit of these methods is an increased accuracy as they integrate the physical damage modelling and simulation with the actual maintenance actions required during the operational cycles off the designed vehicles, but a salient feature in these more advanced methods is that they require a lot of computational time and therefore is more challenging to cover all operating scenarios. Especially in the stage of vehicle design, this is important since the



(a) (b)

Figure 2. Example of result from a more 'purely' engineering approach. (a) RCF concentrations depicted by Nr (b) Rail profile evolution due to wear by vehicle and maintenance actions

'track-friendliness' of a wagon should not be limited to simulating a particular set of scenarios. An example of results from a pure engineering approach is depicted in Figure 2. It shows the evolution of rail surface damage modelled because of vehicle-induced and maintenance-induced wear and Rolling Contact Fatigue over an accumulated tonnage of 100 MGT (typically a period of 3-4 years in the Swedish iron-ore line).

Overall, engineering approaches tend to be relatively rigid in their methodology, i.e., they require meticulous modelling of all phenomena from vehicle-track interaction and maintenance strategies to costs. They also require extensive inputs in the calculation stage, being a 'Bottom-up' approach. While they are suitable to obtain physical indicators governing track deterioration, it can be quite difficult to link them to costs using simple linear relationships since cost modelling involve several non-linear components such as availability of personnel, workshops, etc which are difficult to model using purely engineering-based approaches. Therefore, some works also define relative 'track-friendliness' at the vehicle design stage by using only physical outputs such as ($T\gamma$) as seen in [10]. However for cost relationships, a 'purely' engineering based approach may not be suitable.

2.2 Econometric approach

Figure 1b illustrates a 'pure' econometric approach where basic characteristics of vehicle, track and operational variables are taken as inputs (axle load, sections). However, they are also complemented with a detailed set of section-wise cost data available from historical actions of maintaining and replacing track components. This essentially accounts for a wide set of non-linear cost components derived from prior experience, which was otherwise absent in the engineering approaches. Work done by Andersson et al. [11] in UK, Bugarinovic et al. [12] in Serbia and Gaudry et al. [13] in France are some examples of econometric approaches to guide track access pricing strategies. They provide results in the form of elasticity of track renewal costs with respect to usage by traffic classes using different regression models. 'Track usage' in these approaches are generally expressed in terms of gross-tonnes passage, regardless of the wagon designs that pass through. A simple example for this approach is the Translog regression model used to model costs in [13]:

$$ln(C) = \beta_0 + \sum_{k}^{r} \beta_k ln(X_k) + \sum_{i}^{r} \sum_{j}^{r} \beta_{ij} ln(X_i) ln(X_j) \quad (2)$$

Here C refers to cost data and X refers to operational variables such as traffic class, axle loads, etc. β refer to coefficients used to fit the available cost data C with the variables. The first term in equation (2) corresponds to fixed costs, the second term refers to the effect of variables and the third refers to the effect of interdependency between the variables on cost *C*. Several other regression models are also in use. Typically, many sample sections are taken with *C* and *X* known. The calculation of coefficients β that ensures the best fit between C and X using methods such as least squares approximation give a cost relationship. This makes it a 'Top-down' approach since the calculation already starts with system-wide costs. This is contrast to the simpler linear coefficients approximated in the engineering approach seen earlier.

While this approach tends to give a realistic cost estimate (*C*) for the infrastructure manager with change in payload, age of track components, etc (represented by *X*), they do not necessarily estimate potential savings that can be achieved with more 'track-friendly' wagon designs. This is so since the impact of vehicle design is largely absent in the econometric methodologies. They are more reliable in guiding pricing strategies with incremental changes in tonnage, running distance, etc for the existing traffic and are generally unable to guide vehicle designers to manufacture more 'track-friendly' wagons. However, within the context of the present work, one of the main objectives of the UCM2.0 is to incentivise wagon designs that cause less damage to track by providing a cost calculation tool that can guide manufacturers during the vehicle design stage. Therefore, a purely econometrics-based approach is not suitable.

3. Hybrid approach

In the previous section, two different approaches to propose effective track access pricing strategies were studied. Both approaches came with their own set of advantages and challenges. Within the context of developing 'Universal Cost Model 2.0', the proposed cost relationship should:

- include the effect of innovative vehicle designs on costs to be borne by the infrastructure manager in lieu of its passing.
- give a reasonable estimate of expected costs and a good estimate of the relative difference between different solutions that arise due to track damage by wagon designs.
- be presentable in the form of a simple tool for the infrastructure managers to differentiate various traffic class to assign track access charges.

While the first requirement presents a case for using an engineering approach, the second favours an econometric approach. Therefore, for UCM 2.0, a hybrid approach that combines the advantages of both approaches has been proposed.

Figure 3 illustrates a simple hybrid approach built from elements of both engineering and econometric approaches in Figure 1. Hybrid approaches have previously been studied such as in the recent work by Smith et al [14]. The more advanced engineering approaches are typically not considered in a hybrid approach to ensure more operating scenarios are considered at the vehicle design stage. The cost modelling as depicted by the diagram consists of two steps. To simplify the hybrid approach as much as possible, a clear interface is presented between the cost modeling and the engineering calculations in the figure. Econometric models on that are then simplified as much as possible, linking them to specific maintenance actions, in order to create a streamlined simulation process where the economic results can be directly linked to the simulation results.

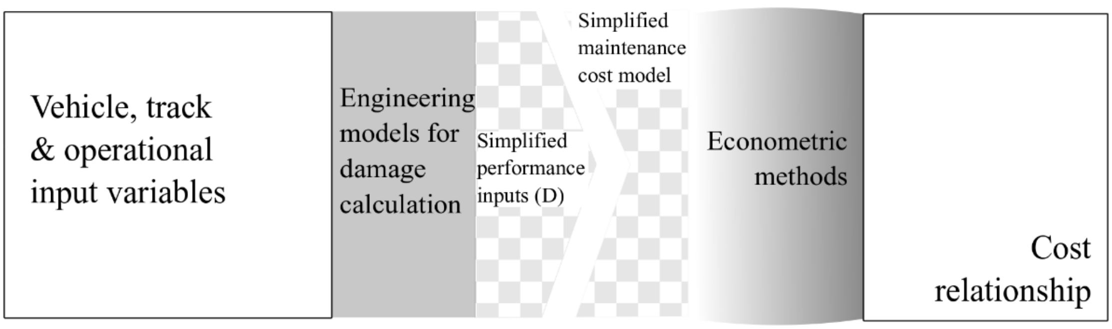


Figure 3. General example of a simple hybrid approach

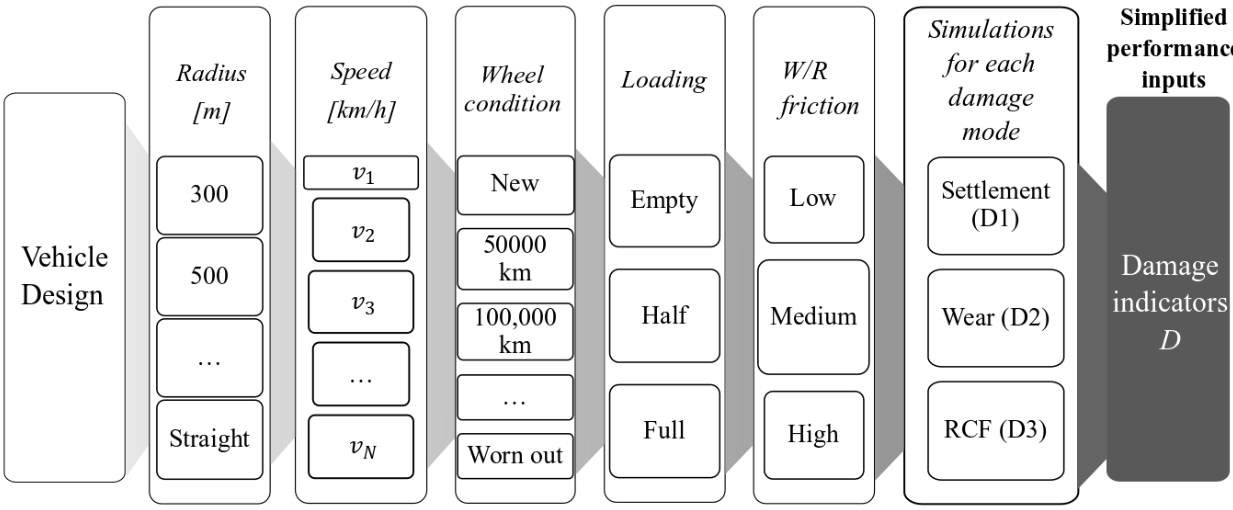


Figure 4. Engineering outputs constituting the first step of the hybrid approach

Initially, simulations are performed for a matrix of intersecting operating scenarios depicted in Figure 4 to obtain engineering outputs. At the end of this step, damage contributions *D* corresponding to each damage mode '*a*' is obtained. For the damage mode of rail surface damage for instance, $D_{wear} = T\gamma$. The cost relationship in step 2 of the hybrid approach then takes the form:

$$ln(C) = \beta_0 + \sum_{a=1}^{A} \beta_\alpha ln(D_{ai}) + \sum_{a=1}^{A}\sum_{b=a}^{A} \beta_{ab} ln(D_{ai}) ln(D_{bi}) + \sum_{k=1}^{K} \beta_k ln(X_{ki}) + \sum_{k=1}^{K}\sum_{l=a}^{K} \beta_{kl} ln(X_{ki}) ln(X_{li}) + \sum_{a=1}^{A}\sum_{k=1}^{K} \beta_{ak} ln(X_{ai}) ln(X_{ki}) + e \quad (3)$$

In equation (3), the damage contributions *D* account for the effect of vehicle design. This is input into an econometric model in step 2 along with other track variables *X* to obtain the form like the one seen in equation (2). However, cost modelling now includes the effect of vehicle design on track-friendliness due to the presence of damage variables (*D)*.

This approach consisting of two steps brings the balance between the modelling of vehicle design in reflecting its 'track-friendliness' and at the same time capturing of the non-linear cost components that constitute typical cost functions used to estimate maintenance. It must be noted however that the Hybrid approach itself can vary depending on how 'pure' engineering or econometric approaches are used in the respective steps. It is possible to use simpler models on both engineering and econometric steps and at the same time more advanced models in either steps. This must be decided on an application-basis depending on whether the whole network/traffic is studied or only specific sections/ traffic classes.

From UCM2.0 standpoint that aims to provide general guidance to vehicle manufacturers regarding the track-friendliness of their prospective vehicle designs (which often are purchased by diverse networks across the world), maximum operating scenarios need to be considered in the design stage. This calls for prioritizing general trends in the track-friendly behaviour of vehicle designs on any given track section rather than an operation-specific analysis. Therefore, the authors recommend the use of simpler econometric models in the hybrid approach at the same time covering a large matrix of operating scenarios as depicted in Figure 4.

4. Conclusions

In this paper different cost modelling approaches are analysed to find the right one for the UCM2.0 user base. A hybrid approach is found to be the most promising, as it can reasonably model Life Cycle Costs incurred by infrastructure managers during the vehicle design stage. This is achieved by calculating the expected costs of track deterioration during the vehicle design stage by considering the vehicle and infrastructure as a single system.

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