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Estimating the marginal maintenance cost of different vehicle types on rail infrastructure

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Abstract

In this paper, we combine engineering and economic methods to estimate the relative maintenance cost of different types of damage on the Swedish rail infrastructure. The engineering method is good at predicting damage from traffic, while the economic method is suitable for establishing a relationship between damage and cost. We exploit the best features of both methods in a two-stage approach and demonstrate its applicability for rail infrastructure charging, based on a sample of 143 track sections comprising about 11,000 km of track. The paper implements for the first time the method previously proposed in Smith et. al. (1), whilst also enhancing the method in several respects. We demonstrate how the estimated relative maintenance costs related to different damage mechanisms can be used to calculate the marginal cost of different vehicle types. The results are relevant for infrastructure managers in Europe who wish to differentiate their track access charges such that each vehicle pays its short run-marginal damage cost, which can support more efficient use of the rail infrastructure and influence vehicle design to minimize system costs.

1.0 Introduction

Operating a train service generates costs for the management of the rail infrastructure. Research on these costs became relevant for European policy after the vertical separation between infrastructure management and train operations in the 1990s, requiring track access charges to be determined. To create an efficient use of the infrastructure, each vehicle should at least pay its short-run marginal cost, which is a requirement supported by EU legislation (see European Commission Directive 2012/34/EC).

One component of the costs incurred by a train service is the wear and other damage of the rail infrastructure. The vertical force on the track created by the weight of the train is a crucial factor for this damage, and ton-km has been the most widely applied charging unit in Europe. However, the damage per ton-km can vary depending on the vehicle type used, where the number of axles and bogie type are important characteristics in this respect. Differentiating the track access charge with respect to variations in damage and cost incurred by different vehicle types creates stronger incentives for developing and running more "track friendly" vehicles and would create an even more efficient use of the infrastructure compared to a ton-km charge. Britain and Switzerland are examples of European countries that have chosen to differentiate their track access charges by vehicle type and ton-km. This type of charge requires an estimation of the marginal cost of different vehicle types running on the rail infrastructure, which is the purpose of this paper.

Different approaches have been used in the literature to determine the marginal cost of wear and other damage. The top-down approach tries to establish a direct relationship between costs and traffic using econometric techniques (see e.g. Wheat et al. (2)), while the bottom-up approach uses engineering models to estimate the damage caused by traffic. In the latter approach, the damages are then linked to maintenance and renewal activities and their respective costs (see e.g. Booz Allen Hamilton and TTCI (3) and Öberg et al. (4)). A combination of these approaches was proposed by Smith et al. (1): a two-stage approach in which simulation methods (engineering models) are used in the first stage to estimate the track damage caused by the rail vehicles running on the railway. The relationship between damage and cost is then established using econometric methods in the second stage. Hanks and Roney in 1982 (5) proposed the use of an engineering model to generate weights for the traffic variable in a statistical model for roadway costs. Their approach resulted in a better model fit and the parameter estimates per traffic volume were used to cost different traffic types. They did not however include the effects on the different degradations modes which is included here and which allows a more detailed understanding of the effects of the vehicle design.

The reason for combining the econometric and engineering approaches in this type of exercise is that they can complement each other. The strength of the former approach is that it uses actual costs and places few restrictions on the elasticities of production; thus, it is able to take account of potential economies of scale in carrying out maintenance work. However, it has difficulties in picking up the complexity of the relationship between different vehicle types and costs – that is, it struggles to provide estimates by vehicles. The engineering approach is on the other hand good at predicting the relative damage caused by different vehicles but has difficulties in linking the damages (caused by traffic) to actual costs.

In this paper we implement the two-stage approach[1] using a dataset comprising 143 track sections in Sweden[2]; whilst also enhancing the methodology. The aim is to demonstrate its practical application, generating new estimates of the marginal maintenance costs for different vehicle types, which in turn can be used to set track access charges. In other words,

[1] Smith et. al. (1) only present an illustrative pilot of the approach, which involved a case study of just one track section.

[2] We make use of a dataset from 2014, which was made available by the Swedish Transport Administration (Trafikverket) as part of a project commissioned in 2015 by the Government Offices of Sweden (Event No N2015/533/TS).

can this approach be seen as a viable approach for infrastructure managers wishing to differentiate their track access charges by vehicle type?

2.0 Methodology

The estimation approach suggested by Smith et al. (1) (depicted in Figure 1 below) consists of two stages. Similar to the bottom-up engineering approach, we perform simulations based on engineering models in the first stage. We use traffic data together with infrastructure characteristics to simulate four different damage mechanisms: track settlement, wear of rails, rolling contact fatigue (RCF), and track component fatigue. From a purely methodological perspective, we therefore make several enhancements, with significantly more detailed vehicle models in the simulation stage; thus, ensuring that fewer assumptions are made on the damage caused by certain vehicles on the track. An extra damage mechanism (track component fatigue) is also included. This damage mechanism may eventually require replacements of components and can be important to consider given that minor replacements are defined as maintenance.

The outputs from the first stage are a set of measures of the different damage types per ton-km for each vehicle type. Apart from differences in traffic between track sections on the rail network, these damage measures can also vary for each section due to the distinct characteristics of the sections such as track geometry and curvature. The measures are then scaled up based on the traffic volume of each vehicle type on the different track sections. In that way, we produce measures on the total track component fatigue, track settlement, RCF and wear of rails, that traffic has caused on a section. We use these damage measures in the second stage, in which a statistical model is formulated where maintenance cost is a function of the damage mechanisms and other cost drivers. Cost elasticities are derived from the statistical model, giving us the relative cost of the damage types. Based on the information from the simulation, we can estimate the marginal cost of the vehicle types.

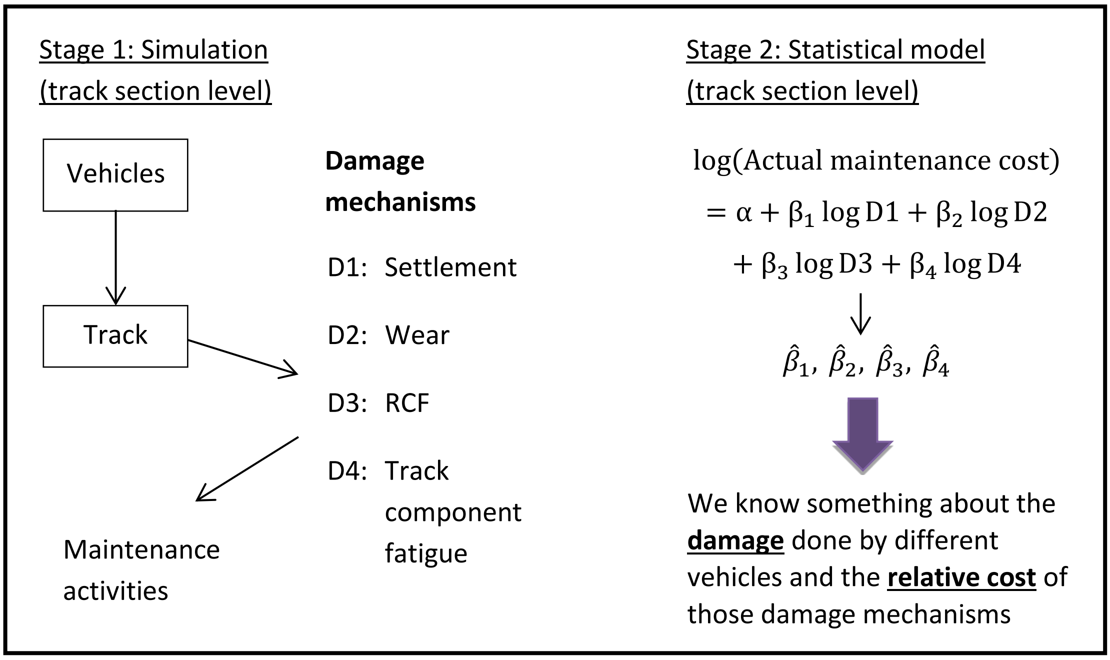

Figure 1: Overview of the methodology (revised figure from Smith et al. (1))

3.0 First stage: simulations

We quantify and calculate the amount of track damage for each of the damage types listed above (Figure 1), using dynamic simulation and the damage prediction models available in the literature. The simulations are performed on 143 track sections in Sweden, which in total comprise about 11 000 km of track. Traffic data from 2014 are used to identify the vehicle types running on each track section. This includes information on the number of vehicles operating on each track section, as well as the vehicle types and their ton-km values.

We use a track model representing concrete sleeper track in the simulations, which is the sleeper type used on most of the track in Sweden (see Chaar and Berg (6) for more information on track flexibility characteristics and its validation). The vehicle models we chose depend on the traffic running on the 143 track sections in this study. According to the traffic data, there were 111 rail vehicles in total operating on these sections in 2014. It is not possible to model each of these vehicles separately. Thus, the vehicles are categorized based on the type of the running gear, vehicle category (freight/passenger), axle load and maximum speed. The chosen categories are presented in Table 1. Moreover, due to time restrictions, we only run simulations for vehicles that comprise more than 9 per cent of a track section's total ton-km. The vehicles that are left out are assigned the damage values from simulated vehicles with the most similar characteristics with respect to damage. All the mentioned models are carefully designed, and the results of the calculations are validated against the field measurements for certain types of the vehicles. To design and run the simulation models the Swedish multibody simulation software GENSYS (7) is used.

Table 1: **Vehicle model categories with their maximum speed**

Categories	Max. speed km/h
Motor coach 4x16 t*	200
Passenger car 4x14 t	160
Motor coach 4x16 t**	200
Motor coach 4x12 t*	140
Motor coach 4x21 t, high centre of gravity**	200
Motor coach with Jacob bogie 3x16.5 t**	160
Motor coach with Jacob bogie 3x12.5 t*	200
Freight loco 6x20 t	120
Freight loco 4x20 t	120
Freight loco 6x30 t	70
Passenger loco 4x19 t	140
Passenger loco 4x19 t	175
Freight wagon (2x22 t or 2x6.5 t)	100
Three-piece bogie 4x30 t	60 (laden)
Three-piece bogie 4x6.5 t	60 (tare)
Y25 bogie 4x22 t	100

* Flexible wheelset guidance, ** Stiff wheelset guidance

Lastly, we use a wheel-rail contact model which consists principally of a wheel-rail geometry module, a creep/spin calculation procedure, and a creep force generator. The theories are described for example in Andersson et al. (8). In this study, the Hertzian solution and Kalkers FASTSIM method is used for the normal and tangential contact problem, respectively.

Inputs needed for the simulation are track geometry and track irregularities, vehicle speeds, wheel and rail profiles, wheel-rail friction level, and axle loads. Data on track geometry has been provided by the Swedish Transport Administration (Trafikverket) and originates from track measurements in 2014. We set the vehicle speed as a function of cant deficiency in a way that maximum allowed cant deficiency can be reached, where the maximum lateral acceleration will be limited according to Banverket (9). The maximum vehicle speed is limited with the permissible speed on each line. In this study, the friction level is assumed to be 0.45 for all the simulations unless the locomotives are equipped with vehicle-based lubrication systems - that is, the Iron-Ore loco used on the Iron ore line in northern Sweden.

Following the method previously developed by the authors (Smith et al (1), pp.623ff), four types of track damage are calculated for each vehicle on each track section: track settlement, track component fatigue, wear of rails and rolling contact fatigue (RCF). To calculate the settlement damage the adapted TUM (Technical University of Munich) settlement calculation model is used:

$$Settlement = A \cdot Q^{1.21} \log \mathrm{N} \tag{1}$$

where N is number of axle passes, Q is the dynamic vertical force at the wheelset (from the simulations, we take the 99,85th percentiles), and A is a constant; (A=1 in the current work).

Internal fatigue damage due to repeated loading is a function of both vertical and lateral track forces. The components affected by the repeated loading are rails, rail pads, rail fasteners, and sleepers. The calculation method is developed by UIC/ORE (10) based on extensive tests and it is complemented by Öberg et al. (4) with a lateral force component – that is, the resulting force on either rail.

$$Track\ component\ fatigue = \frac{1}{n_v} \cdot \sum_{i=1}^{n_v} \left[\sqrt{Q_{tot\_i}{}^2 + Y_{qst\_i}{}^2} \right]^3 \quad (2)$$

where n_v is the number of axles, Q_{tot_i} is the sum of static, quasistatic and dynamic vertical force (from the simulations we take the 99,85th percentiles), and Y_{qst_i} is quasistatic lateral force (RMS value taken from simulation).

Wear of rail and wheel is a function of material properties (steel grade), contact pressure (axle load, wheel-rail profile), sliding velocity (creepage and spin), weather condition and lubrication (track side or vehicle based). To predict the wear on rails, the dissipated energy in the wheel-rail contact patch is calculated. Energy dissipation per meter running distance is calculated as:

$$\bar{E} = F_x \nu_x + F_y \nu_y + M\varphi \quad (3)$$

where, F_x and F_y are longitudinal and lateral creep forces, ν_x and ν_y are longitudinal and lateral creepages, and M is the moment and φ is the spin in the contact patch. In the present study, it is assumed that if the wear values are below 160 J/m, then the wear regime is mild wear and the value of wear damage is neglected (Smith et al., (1)).

To calculate surface initiated cracks due to RCF, again the energy dissipation based theory is used (see Figure 2). Here, first the energy dissipation is calculated and then the RCF index is picked accordingly.

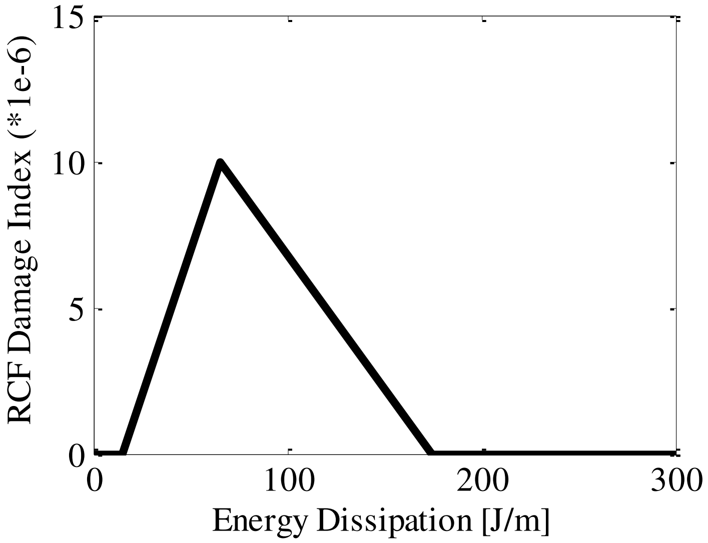

Figure 2: **Rail RCF damage function (Burstow (11))**

It is too time consuming to perform the simulations for all vehicles on the entire length of all track sections. Instead, we use the load collective method (cf. Enblom (12)), which implies that we create 10 different subsection categories as a function of the track curvature. These subsection categories are track segments with radii 0-400m, 400-600m, 600-800m, 800-1000m, 1000-1500m, 1500-2000m, 2000-3000m, 3000-5000m, 5000-10000m and above 10000m. Hence, a track section has many track segments in each subsection category. We choose one segment in each subsection category (measured by the track geometry car) with a track length that is closest to the mean length of all the track segments in its subsection category. The simulated damage on each segment is then scaled up with respect to the total track length of the subsection category the segment belongs to.

All four track damage values are calculated for all the subsection categories on each track section and for every vehicle operating on that specific section. Maximum values are considered for all types of damages. The values are then summed for all axles and scaled based on the contribution of the subsection to the entire track section and normalised by the ton-km values obtained from the traffic data.

4.0 Second stage: Econometric model

With estimates on the damage caused by traffic, we can derive cost elasticities for the damage types using econometric methods. To do so, we need to control for other factors that may influence maintenance costs. More specifically, we formulate costs as a function of a set of variables, where the damage types are the variables of main interest

$$C_i = f(D_{1i}, D_{2i}, D_{3i}, D_{4i}, \boldsymbol{X}_i) \tag{4}$$

where C_i is maintenance costs on $i = 1, 2, \dots, N$ track sections. D_{1i}, D_{2i}, D_{3i}, and D_{4i} are the damage types track settlement, wear of rails, RCF and track component fatigue. $\boldsymbol{X}_i$ is a vector of infrastructure characteristics such as track length and the average age of rails.

The damage measures are based on the total ton-km on each section, which in turn depend on the length of each section. Therefore, to separate track length effects from damage effects, we use damage density variables ($\frac{D_{1i}}{Track\text{-}km_i}, \frac{D_{2i}}{Track\text{-}km_i}$ etc.) along with the track length variable in the model estimations.

We start with the translog model proposed by Christensen et al. (13), which is a second order approximation of a cost (production) function. Both the dependent variable (costs) and the independent variables (damages and infrastructure characteristics) are subject to a logarithmic transformation in this model, which can reduce skewness and heteroscedasticity, problems that may invalidate the statistical inference if not treated correctly. Specifically, we consider A damage types, K network characteristics and M dummy variables, and express the model as

$$lnC_i = \alpha + \sum_{a=1}^{A} \beta_a lnD_{ai} + \frac{1}{2}\sum_{a=1}^{A}\sum_{a=1}^{A} \beta_{aa} lnD_{ai}\, lnD_{ai} +$$

$$+ \sum_{a=1}^{A}\sum_{b=1}^{A} \beta_{ab} lnD_{ai}\, lnD_{bi} + \sum_{k=1}^{K} \beta_k lnX_{ki} + \frac{1}{2}\sum_{k=1}^{K}\sum_{k=1}^{K} \beta_{kk} lnX_{ki}\, lnX_{ki}$$

$$+ \sum_{k=1}^{K}\sum_{l=1}^{K} \beta_{kl} lnX_{ki}\, lnX_{li} + \sum_{a=1}^{A}\sum_{k=1}^{K} \beta_{ak} lnD_{ai} lnX_{ki} + \sum_{m=1}^{M} \beta_m Z_{mi} + v_i \tag{5}$$

where α is a scalar, v_i is white noise and $\boldsymbol{\beta}$ is a vector of parameters to be estimated, and the symmetry restrictions $\beta_{ab} = \beta_{ba}$, $\beta_{kl} = \beta_{lk}$, and $\beta_{ak} = \beta_{ka}$ are used.

5.0 Data

In total, there were 244 track sections in 2014 administered by Trafikverket and their five regional units: Region North, West, East, South and Central. Limited access to up-to-date track geometry data constrains us to analyse a somewhat smaller part of the Swedish railway network. However, the 143 sections in our data set cover 11 000 track-km out of the 14 100 track-km administered by Trafikverket. Hence, the tracks in our data comprise a cross-section of the Swedish rail network with sections from north to south and with large variations in traffic and costs. Descriptive statistics of the data are provided in Table 2.

The costs for rectifying track damage are defined as either maintenance or renewal costs. The former are costs for activities conducted to preserve the railway’s assets, while the latter are costs for major replacements (minor replacements are defined as maintenance). Given the lumpy nature of renewals, and that we only have access to data for one year (2014), we limit our analysis to maintenance costs only.

Information on the infrastructure characteristics has been collected from Trafikverket and comprises data on track length, rail age and quality classification (track geometry requirements linked to maximum line speed allowed). The statistics of the damage measures in Table 2 are based on the total damages incurred by the vehicles on each track section.

Table 2: Descriptive statistics, obs. from 143 track sections

	Median	Mean	St. dev.	Min	Max
Maintenance costs, million SEK	14.25	19.66	17.86	0.87	108.67
Wear, index*	2.21E+12	8.22E+14	5.32E+15	8.26E+06	5.52E+16
RCF, index*	5.58E+08	6.55E+11	3.93E+12	4.46E+05	3.37E+13
Settlement, index*	7.46E+14	5.87E+15	2.75E+16	4.61E+11	2.54E+17
Track component fatigue, index*	3.91E+24	1.85E+28	1.44E+29	4.11E+21	1.38E+30
Wear density**	1.09E+08	2.43E+08	4.38E+08	2.10E+06	2.75E+09
RCF density**	3.15E+05	5.12E+05	7.46E+05	1.02E+04	7.84E+06
Settlement density**	2.96E+12	3.66E+12	3.30E+12	4.89E+10	2.45E+13
Track component fatigue density**	2.18E+22	3.37E+22	4.87E+22	3.83E+20	4.80E+23
Route length, km	50.17	60.86	40.59	5.97	215.95
Track length, km	63.95	78.79	52.41	7.84	251.39
Average quality class***	2.77	2.74	1.08	1.00	5.02
Average age of rails	21.2	22.4	9.4	4.1	51.3
Million ton density	4.23	7.68	8.24	0.11	45.72
Region West	0	0.20	0.40	0	1
Region North	0	0.13	0.33	0	1
Region Central	0	0.17	0.38	0	1
Region South	0	0.29	0.45	0	1
Region East	0	0.22	0.42	0	1

* See section 3. See also Smith et al. (1) for more details on the Wear, RCF and Settlement indices, whilst Öberg et al. (4) provides details on the track component fatigue index. ** Damage index per track-km, *** Track quality class ranges from 0-5 (from low to high line speed), but 1 has been added to avoid observations with value 0.

6.0 Results

The models are estimated using ordinary least squares (OLS) and the results are presented in Table 4. All estimations are carried out with Stata 12 (StataCorp (14)).

As a starting point, we examine the correlation coefficients between the different damage mechanisms (see Table 3). Track settlement covaries strongly with track component fatigue (the correlation coefficient is 0.95) and with RCF (0.82). The correlation coefficient for wear and track settlement is the lowest (0.72). We therefore also estimate our models using only these two damage mechanisms (*Model 1b*), as we expect them to capture the effects of RCF and track component fatigue to a large extent.

Table 3: Correlation coefficients

	Wear_den.	RCF_den.	Settl._den.	Comp._den.
Wear_den.	1.0000			
RCF_den.	0.7228	1.0000		
Settl._den.	0.7155	0.8157	1.0000	
Comp._den.	0.8123	0.7752	0.9471	1.0000

We start with a full translog model and test linear restrictions of the parameter estimates using F-tests, which results in the models presented in Table 4. We include a set of control variables which turn out to have coefficients that are in line with the literature (see e.g. Wheat et al. (2) and Odolinski and Nilsson (15)). Including Qual_ave (linked to line speed) can pick up quality aspects other than wear and damage caused by vehicles' line speed, for example maintenance strategies/priorities associated with line speed. We also include rail age to control for maintenance costs that are due to previous use of the track rather than the damage caused by traffic in 2014. A track length variable is included to separate track length effects from damage effects. However, we do not expect track length will pick up scale effects *per se* in this study (groups of track sections belong to maintenance contract areas), but is included as the length of a section may lack a one-to-one relationship with other infrastructure characteristics. Moreover, we include dummy variables for maintenance regions, as these may pick up differences in the management of the sections.

Table 4: Estimation results, Model 1

	Model 1a		*Model 1b*	
	Coef.	Rob. Std. Err.	Coef.	Rob. Std. Err.
Cons.	16.4675***	0.1030	16.4779***	0.1024
Wear_den.	0.1079	0.0718	0.1182*	0.0714
RCF_den.	0.0485	0.0805	-	-
Settl._den.	0.0996	0.0983	0.1345*	0.0719
Track_length	0.9303***	0.0582	0.9385***	0.0588
Qual_ave	-0.0428	0.2185	-0.0237	0.2113
0.5Qual_ave^2	-0.9850*	0.5132	-1.0099*	0.5205
Rail_age	0.2575*	0.1337	0.2699**	0.1340
Settl._den.Qual_ave	-0.5618***	0.1189	-0.5685***	0.1188
Region_West	0.3264**	0.1429	0.3254**	0.1431
Region_North	0.0442	0.1903	0.0395	0.1886
Region _Central	-0.2981**	0.1500	-0.2933*	0.1491
Region _South	-0.2179	0.1395	-0.2173	0.1395
Mean VIF	2.73		2.31	
R^2	0.70		0.70	
Adj. R^2	0.67		0.67	

We transform all data by dividing by the sample median prior to taking logs. In that way, the first order coefficients can be interpreted as cost elasticities at the sample median. See Table 7 in the appendix for definitions of the variables.

Note: ***, **, *: Significance at 1 %, 5 %, and 10 % level, respectively

Higher speeds imply stricter requirements on track quality (track geometry). This may increase the propensity to rectify the settlement damage caused by the vehicles. Indeed, the interaction term between Settlement and Qual_ave is negative, which suggests that the cost impact of settlement is lower for low line speeds (high Qual_ave value) compared to high line speeds (low Qual_ave value). We calculate the cost elasticities with respect to Qual_ave at the observed levels of the variables (which is $\hat{\gamma}_{iQual.} = \hat{\beta}_5 + \hat{\beta}_6 lnQualave_i + \hat{\beta}_8 lnSettlement_i$), which shows that the elasticities are positive for low levels of Qual_ave (high linespeed) and turn negative for high levels of the variable (low line speed). However, its mean value is 0.2240 and not statistically significant (p-value 0.173).

The coefficients for rail age and track length are statistically significant and have the expected signs. Turning to the cost elasticities with respect to the damage measures in Model 1a, we note that these are 0.1079, 0.0485 and 0.1554 for wear, RCF and settlement, respectively. None of these estimates are statistically significant. In Model 1b we drop RCF due to its high correlation coefficient with settlement, which generates a higher estimate for settlement. The coefficients for wear and settlement are now 0.1182 and 0.1910 and statistically significant at the 10 per cent level. The sum of the first order coefficients is 0.3118 and 0.3092 in Model 1a and Model 1b, respectively, indicating that the cost impact of RCF is to a large extent picked up by the estimates for wear and settlement.

6.1 Marginal costs

We calculate the marginal cost per damage unit (see section 6.1.1) and link these costs to vehicle types, based on the amount of damage per ton-km each vehicle has caused according to the simulations. In that way, we produce a marginal cost per ton-km, which is the preferred charging unit (see section 6.1.2).

6.1.1 Marginal cost per damage unit

In the marginal cost estimation, we use the estimated cost elasticities for wear and settlement evaluated at the sample median (0.1182 and 0.1345, respectively).[3] Marginal costs that are based on the non-significant cost elasticities (including RCF) in Model 1a are presented in Table 8 in the appendix.

The marginal cost of a damage mechanism j is formulated as

[3] We refrain from using the track section specific elasticities for settlement (created by the interaction with quality class) as this would make the marginal cost for vehicle types more dependent on which track sections the vehicles ran on during 2014.

$$MC_{ij}\ per\ damage\ unit = \frac{\partial C_i}{\partial D_{ij}} = \frac{D_{ij}}{C_i}\frac{\partial C_i}{\partial D_{ij}}\frac{C_i}{D_{ij}} = \frac{\partial lnC_i}{\partial lnD_{ij}}\frac{C_i}{D_{ij}} \tag{6}$$

where D is any of the four types of damage noted above. Hence, from equation (6) we can express the marginal cost estimate at track section i as

$$MC_{ij}\ per\ damage\ unit = \hat{\gamma}_j \cdot \widehat{AC}_{ij} \tag{7}$$

where $\hat{\gamma}_j$ is the estimated cost elasticity ($\frac{\partial lnC_i}{\partial lnD_{ij}}$) of damage mechanism j. $\widehat{AC}_{ij}$ is the average cost ($\frac{\hat{C}_i}{D_{ij}}$), where $\hat{C}_i$ is predicted costs specified as

$$\hat{C}_i = \exp\left[\ln(C_i) - \hat{v}_i + 0.5\hat{\sigma}^2\right] \tag{8}$$

Equation (8) derives from the double-log specification and the assumption of normally distributed residuals.

To obtain a marginal cost estimate that can be used as a policy measure (i.e. a track access charge) for all track sections included in this study, we use a weighted marginal cost for the 143 track sections, according to equation (9) below, which is in line with the wider literature (see Wheat et al. (2) and Odolinski and Nilsson (15)). Specifically, we use each track section's share of total damage as weights and multiply with each section's marginal cost per damage unit. Taking the sum over all track sections produces a weighted marginal cost estimate that generates the same income as if each section's marginal cost would be used.

$$MC_j^W per\ damage\ unit = \sum_i \left[MC_{ij}\ per\ damage\ unit \cdot \frac{D_{ij}}{\sum_i D_{ij}}\right] \tag{9}$$

The average cost, the marginal and weighted marginal costs are presented in Table 5. These costs become quite low as they are estimates per total damage.

Table 5: Average and marginal costs per damage unit, SEK in 2014 prices

	Variable	Mean	Std. Err.	[95% Conf.	Interval]
Average cost	Wear	5.62E-03	7.90E-04	4.05E-03	7.18E-03
	Settlement	2.56E-07	5.08E-08	1.56E-07	3.57E-07
Marginal cost	Wear	6.64E-04	9.34E-05	4.79E-04	8.48E-04
	Settlement	3.45E-08	6.84E-09	2.10E-08	4.80E-08
Weighted marginal cost	Wear	1.41E-04	-	-	-
	Settlement	9.37E-09	-	-	-

The weighted marginal cost for settlement is lower than the cost for wear, even though their respective cost elasticities are similar. The reason is that the damages have different units, generating an average cost of settlement that is much lower than the average cost of wear. In the next section, these marginal costs are converted to estimates per ton-km to make them comparable with marginal cost estimates in the literature.

6.1.2 Marginal cost per ton-km and vehicle type

We use the weighted marginal cost per damage unit (eq. 9) and multiply with the damages per ton-km for each vehicle. This calculation normalises the differences in units between the damage mechanisms. The damages per ton-km are weighted using the sum of ton-km over all track sections for each vehicle type – that is, the weights are a vehicle type's share of gross ton-km on track section i with respect to the vehicle type's total gross ton-km.

$$MC_{jv}^{W} per\ tonkm = MC_{j}^{W} per\ damage\ unit \cdot \sum_{i} \frac{D_{ijv}}{GTkm_{iv}} \cdot \frac{GTkm_{iv}}{(\sum_{i} GTkm_{iv})} \qquad (10)$$

For example, freight loco 4x20 t, V_{max} 120 km/h, has a weighted average wear per ton-km at 21.75 and a weighted average settlement per ton-km at 743 656. Its total marginal cost per ton-km is therefore

$$1.41\text{-}E04 * 21.75 + 9.37E\text{-}09 * 743\ 656 = 0.0100$$

where 1.41-E04 and 9.37E-09 are the weighted marginal cost for wear and settlement, respectively (see eq. 9 and Table 5). The weighted average damage per ton-km and weighted marginal cost per ton-km for each vehicle type are presented in Table 6, where the example above is in bold text (the damage measures for RCF are presented in Table 9 in the appendix).

Table 6: Damages and marginal costs (MC_{jv}^{W}) per ton-km and vehicle type

Vehicle type	Wear per ton-km[a]	Settlement per ton-km[a]	MC wear[b] (eq.10)	MC settlement[b] (eq.10)	Total MC[b]
Motor coach 4x21 t, V_{max} 200 km/h *	209.76	995 468	0.0295	0.0093	0.0389
Three-piece bogie 4x30 t, V_{max} 60 km/h, laden	97.56	867 067	0.0137	0.0081	0.0219
Passenger car 4x14 t, V_{max} 160 km/h	57.34	741 423	0.0081	0.0069	0.0150
Freight loco 6x30 t, V_{max} 70 km/h	36.85	1 001 992	0.0052	0.0094	0.0146
Freight loco 6x20 t, V_{max} 120 km/h	36.90	945 300	0.0052	0.0089	0.0141
Motor coach 4x16 t, V_{max} 200 km/h**	41.46	852 697	0.0058	0.0080	0.0138
Passenger Loco 4x19 t, V_{max} 175 km/h	40.69	740 151	0.0058	0.0070	0.0128
Three-piece bogie 4x6.5 t, V_{max} 60 km/h, tare	50.22	602 992	0.0071	0.0056	0.0127
Passenger Loco 4x19 t, V_{max} 140 km/h	40.85	748 934	0.0057	0.0069	0.0127
Motor coach, Jacob bogie 3x16.5 t, V_{max} 160 km/h**	53.58	476 803	0.0075	0.0045	0.0120
Y25 bogie 4x22 t, V_{max} 100 km/h, laden	30.32	795 901	0.0043	0.0075	0.0117
Freight wagon 2x6.5, V_{max} 100 km/h, tare	49.75	383 151	0.0070	0.0036	0.0106
Motor coach, Jacob bogie 3x12.5 t, V_{max} 200 km/h***	33.73	571 887	0.0048	0.0054	0.0101
Freight loco 4x20 t, V_{max} 120 km/h	**21.75**	**743 656**	**0.0031**	**0.0070**	**0.0100**
Motor coach 4x12 t, V_{max} 140 km/h***	21.12	668 032	0.0030	0.0063	0.0092
Freight wagon 2x22 t, V_{max} 100 km/h, laden	26.48	464 017	0.0037	0.0043	0.0081
Motor coach 4x16 t, V_{max} 200 km/h***	12.03	676 894	0.0017	0.0063	0.0080
All vehicles, weighted averages	44.10	751 142	0.0062	0.0070	0.0132

[a] $\sum_i \frac{D_{ijv}}{GTkm_{iv}} \cdot \frac{GTkm_{iv}}{(\sum_i GTkm_{iv})}$ (the last part of eq. 10), [b] SEK in 2014 prices, * High centre of gravity and stiff wheelset guidance, ** Stiff wheelset guidance, ***Flexible wheelset guidance.

Using each vehicle type's share of total ton-km as weights, and multiplying by its marginal cost from eq. 10, we get a weighted marginal cost for the entire sample: SEK 0.0062 for wear and

SEK 0.0070 for settlement, which sums to SEK 0.0132 (Table 6). Our focus in this paper is primarily to use the results to compare the relative damage cost of different vehicles. However, it is also interesting to compare the overall (average) level of marginal costs with the available previous estimates using Swedish data. Andersson (16) and Odolinski and Nilsson (15) used a single stage econometric approach (costs regressed on tonnage), and generated marginal costs of SEK 0.0080 and SEK 0.0094 respectively (in 2014 prices); thus our estimates are of a similar order of magnitude, but roughly 40-60% higher.

The vehicles in Table 6 are ordered after the highest marginal cost, showing that Motor coach 4x21 t, V_{max} 200 km/h (stiff wheelset guidance and high centre of gravity) is assigned a marginal cost at SEK 0.0389. The other estimates stretch from SEK 0.0080 to SEK 0.0219, indicating rather differentiated marginal costs. Interestingly, a tare freight wagon 2x6.5t, V_{max} 100km/h, has a higher marginal cost (SEK 0.0106) than its laden counterpart (2x22t, V_{max} 100km/h), which has a marginal cost at SEK 0.0081. The reason for this relationship is that the tare freight wagon has a factor 1.88 higher wear per ton-km (weighted average) than the laden freight wagon (a lighter vehicle "moves around" more on the track, creating a higher wear)[4], while the laden wagon only has a factor 1.21 higher settlement per ton-km than the tare wagon (cf. Table 6). Hence, given our cost estimates for the damage types (SEK 0.0062 and 0.0070 per ton-km for wear and settlement, respectively), the total marginal cost is higher for the tare wagon in this case.

7.0 Discussion

The relative marginal maintenance costs by vehicle type in this paper differ from those generated by Öberg et al. ((4), p. 58-59). One reason is that Öberg et al. (4) use estimated

[4] This is also the case in Öberg et al. (4), where simulations were made for tare and laden freight wagons with a Y25 bogie, where the former had a higher wear and RCF damage compared to the latter.

average cost shares to weight the different damage mechanisms. These are estimates made by the Swedish Rail Administration based on expert judgement. Settlement was estimated to be responsible for 25 per cent, wear and RCF was attributed 40 per cent, while component fatigue was allocated 35 per cent of costs. Their approach makes the underlying assumption that the share of a damage mechanism's average cost is equal to its share of marginal cost, which need not be the case.

A significant contribution of our paper is that we use cost elasticities estimated from empirical data to produce these marginal cost shares for the different damage mechanisms, which has not previously been done[5]. There are also significant differences between the damage estimation approaches in the study by Öberg et al. (engineering approach) and our paper. They perform their simulations on a "representative" track with a curve distribution that was weighted by the actual traffic volume on different curve zones on 5000 km of tracks, which is about 35 per cent of the total network length. Added to this, their simulations were carried out on perfect track with track gauge 1435 and no track irregularities, except for freight vehicles, which were simulated on a track with irregularities based on measurements on a 500 m section of the Swedish main line. Hence, both the simulation strategy and the cost calculations in Öberg et al. (4) differ from our paper, as we perform simulations based on actual curvature and track measurements of irregularities on each of the 143 track sections (comprising almost 80 per cent of the total network length), to predict the actual damage from traffic during a year and relate it to actual costs during the same year.

Finally, it should be pointed out that the cost elasticities we use for wear and settlement in the marginal cost estimation are considered to also capture effects of RCF and track component fatigue. Indeed, this seems to be verified from the results (at least for RCF) as the

[5] As noted, Smith et. al. (1) piloted the approach, but for a small, sub-set of vehicle types on only part of the network, for illustrative purposes.

weighted MC for all damage types from Model 1a is SEK 0.0134, which is almost the same estimate generated by Model 1b (SEK 0.0132). However, in our application, the relationships between the vehicles in Table 6 are rather similar to the relationships generated by Model 1a (see Table 9) which include the cost impact from RCF. This can be summarized by the rankings of the vehicle types with respect to their total marginal cost; the correlation coefficient between the different rankings is 0.74). Generally, not being able to isolate the cost impact of each damage mechanism is a potential limitation of our approach, although as noted that the correlation between the rankings is still reasonably high in our case.

8.0 Conclusion

This paper contributes to the existing literature by making the first implementation, with a new and substantive dataset, of the two-stage economic-engineering method proposed by Smith et al. (1). We show that the approach can produce useful estimates of the relative cost of damage mechanisms, that can be informative for infrastructure managers in Europe. Specifically, by combining engineering and econometric approaches, we have estimated marginal costs for the vehicle types running on the Swedish railway network based on data for 143 track sections and 11,000 km of track in Sweden. A significant contribution of our paper is that we use cost elasticities estimated from empirical data to weight the different damage mechanisms for different vehicle types, which has not previously been done. The methodology has also been enhanced in several respects, in particular with more detailed vehicle models.

The paper demonstrates the power of combining the best aspects of engineering methods (good at estimating damage) and economic/econometric approaches (good at estimating cost relationships). Given past challenges in rail technology-based research to obtain reliable estimates of the cost implications of different vehicle designs based on engineering approaches, this research offers an attractive new way to capture of the relative cost of different damage mechanisms, and thus improve our understanding of how rail infrastructure costs vary with vehicle design.

The results indicate a substantial variation in the marginal cost per ton-km for different vehicle types running on the Swedish railway, which is due to differences in the damage done by the vehicles and the relative cost of the damage mechanisms. The research is therefore also important for informing and enhancing track access charging regimes such that railways face the correct price signals to run and develop track-friendly vehicle designs that minimise system costs.

One limitation is that correlation between some of the damage mechanisms meant that it was not possible to fully isolate the separate impact of all the damage types; though it was possible to obtain reasonable overall estimates because of correlations between the damage mechanisms. This issue could be resolved through utilising data over time, thus both increasing the sample size and controlling for unobserved section-specific effects; in turn improving the precision of our estimates. Future research should also focus on how best to implement the results of this approach in respect of access charging, and in particular whether route-based charging may be appropriate.

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Appendix

Table 7: Definition of variables

Wear_den.	=	ln(wear density)
Wear_den.^2	=	0.5*ln(wear density)*ln(wear density)
RCF_den	=	ln(RCF density)
Settl._den	=	ln(Settlement density)
Comp._den,	=	ln(Track component fatigue density)
Comp._den.^2	=	0.5*ln(Track comp. fatigue density)*ln(Track comp. fatigue density)
Wear_den.Settl._den	=	ln(wear density)*ln(settlement density)
Wear_den.Com._den.	=	ln(wear density)*ln(Track component fatigue density)
Track_length	=	ln(track length)
Qual_ave	=	ln(average quality class)
Qual_ave^2	=	0.5*ln(average quality class)*ln(average quality class)
Rail_age	=	ln(average age of rails)
Settl._den.Qual_ave	=	ln(settlement density)*ln(average quality class)
Region_West	=	Dummy for region West
Region_North	=	Dummy for region North
Region_Central	=	Dummy for region Central
Region_South	=	Dummy for region South
Region_East	=	Dummy for region East

Table 8: Model 1a - Average and marginal costs per damage unit, SEK in 2014 prices

	Variable	Mean	Std. Err.	[95% Conf.	Interval]
Average cost	Wear	5.60E-03	7.84E-04	4.05E-03	7.15E-03
	RCF	1.65E+00	2.12E-01	1.23E+00	2.07E+00
	Settlement	2.58E-07	5.27E-08	1.54E-07	3.63E-07
Marginal cost	Wear	6.04E-04	8.46E-05	4.37E-04	7.72E-04
	RCF	8.02E-02	1.03E-02	5.99E-02	1.01E-01
	Settlement	2.57E-08	5.25E-09	1.53E-08	3.61E-08
Weighted marginal cost	Wear	1.29E-04	8.21E-06	1.13E-04	1.45E-04
	RCF	2.34E-02	1.49E-03	2.04E-02	2.63E-02
	Settlement	6.94E-09	4.43E-10	6.07E-09	7.82E-09

Table 9: Model 1a - Marginal costs per ton-km and vehicle type (based on non-statistically significant cost elasticities)

Vehicle type	Wear per ton-km	Settlement per ton-km	RCF per ton-km	Total MC[a]	Ranking	Ranking. in Model 1b
Motor coach 4x21 t, V_{max} 200 km/h*, **	209.76	995 468	0.09	0.0361	1	1
Three-piece bogie 4x30 t, V_{max} 60 km/h, laden	97.56	867 067	0.26	0.0247	2	2
Freight wagon 2x6.5, V_{max} 100 km/h, tare	49.75	383 151	0.34	0.0169	3	12
Passenger car 4x14 t, V_{max} 160 km/h	57.34	741 423	0.14	0.0159	4	3
Freight loco 6x20 t, V_{max} 120 km/h	36.90	945 300	0.11	0.0139	5	5
Motor coach 4x16 t, V_{max} 200 km/h**	41.46	852 697	0.11	0.0138	6	6
Three-piece bogie 4x6.5 t, V_{max} 60 km/h, tare	50.22	602 992	0.12	0.0134	7	8
Motor coach, Jacob bogie 3x16.5 t, V_{max} 160 km/h**	53.58	476 803	0.13	0.0132	8	10
Freight loco 6x30 t, V_{max} 70 km/h	36.85	1 001 992	0.05	0.0128	9	4
Passenger Loco 4x19 t, V_{max} 175 km/h	40.69	740 151	0.07	0.0127	10	7
Passenger Loco 4x19 t, V_{max} 140 km/h	40.85	748 934	0.10	0.0121	11	9
Motor coach, Jacob bogie 3x12.5 t, V_{max} 200 km/h***	33.73	571 887	0.14	0.0116	12	13
Y25 bogie 4x22 t, V_{max} 100 km/h, laden	30.32	795 901	0.08	0.0114	13	11
Freight loco 4x20 t, V_{max} 120 km/h	21.75	743 656	0.07	0.0097	14	5
Freight wagon 2x22 t, V_{max} 100 km/h, laden	26.48	464 017	0.09	0.0088	15	16
Motor coach 4x12 t, V_{max} 140 km/h***	21.12	668 032	0.05	0.0085	16	15
Motor coach 4x16 t, V_{max} 200 km/h***	12.03	676 894	0.05	0.0073	17	17
All vehicles, weighted average (marginal cost in parenthesis)	44.10 (0.0057)	751 142 (0.0052)	0.11 (0.0026)	0.0134	Correlation coefficient between rankings: 0.74	

[a] SEK in 2014 prices * High centre of gravity, ** Stiff wheelset guidance, ***Flexible wheelset guidance