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The impact of cumulative tons on rail infrastructure maintenance costs

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Abstract

In this paper the cost impact of rail infrastructure usage in Sweden is estimated, using a measure of the cumulative tons experienced by the tracks since they were renewed. The cost elasticity with respect to this measure is compared to the corresponding estimate from annual tons, a standard measure of output in the literature. The cumulative ton measure generates a higher cost elasticity compared to annual tons, and increases substantially when tracks have been extensively used. The results are informative for the Swedish infrastructure manager that needs to strike a balance between maintenance and renewals; the expected cost of maintenance with respect to accumulated use can be compared to the expected cost of a renewal.

Keywords: rail infrastructure, maintenance costs, and cumulative tons

JEL Codes: R48, L92

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In this paper the cost impact of rail infrastructure usage in Sweden is estimated, using a measure of the cumulative tons experienced by the tracks since they were renewed. The cost elasticity with respect to this measure is compared to the corresponding estimate from annual tons, a standard measure of output in the literature. The cumulative ton measure generates a higher cost elasticity compared to annual tons, and increases substantially when tracks have been extensively used. The results are informative for the Swedish infrastructure manager that needs to strike a balance between maintenance and renewals; the expected cost of maintenance with respect to accumulated use can be compared to the expected cost of a renewal.

1.0 Introduction

An important part of the literature on rail infrastructure costs deals with how rail maintenance is affected by traffic. Annual ton density is the output variable used in most econometric approaches that try to establish a direct relationship between traffic and costs. Knowledge on this relationship is for example crucial when setting track access charges for the train operators, charges that became necessary in many European countries after the vertical separation between infrastructure management and train operations in the 1990s. Hence, the impact of annual tons on rail infrastructure maintenance costs in Europe has been extensively analysed. Nilsson and Johansson (2004), Andersson (2008) and Odolinski and Nilsson (2015) are examples of studies using data on the Swedish railway network, while the studies in Link et al. (2008) and Wheat et al. (2009) include a set of other countries in Europe. In this study we address a more fundamental aspect of traffic and costs, namely the impact of annual use (tonnage) is contrasted to the accumulated tonnage since the rails were originally laid.

Empirical studies of cumulative tons and its impact on maintenance costs is however scarce. One notable example is the study by Gaudry et al. (2015) which uses a cumulative ton measure on cross section data to test a framework for optimization of maintenance and renewals. Still, no comparison with annual tons is made.

Indeed, the effect cumulative use has on maintenance costs is a crucial input in a maintenance and renewal strategy, where a proper balance between these activities needs to be found. The reason is that tracks have a limited expected service life that is economically justified. The length of this service life is to a large extent dependent on the traffic volume; the deterioration of the tracks increases with the accumulated use, making more maintenance activities necessary in order to sustain the performance of the railway. Eventually, it will be cheaper to renew the tracks rather than to rectify failures that occur on a track that has experienced high levels of traffic over the years.

In order to generate a reliable input in an optimization strategy for maintenance and renewals, a particular purpose of this paper is to consider the most appropriate way to indicate that the infrastructure is worn down over time due to traffic. One way to do so is to use information about rail age. The age of the tracks is at best a first proxy of the network standard, since one section of the network may be very old but not extensively used, while another section may have been rehabilitated recently although it has since been extensively used. Therefore, a fundamental part of this paper concerns the calculation of the cumulative ton measure, which relies on data on past traffic as well as the age of the tracks. Moreover, while tracks may require more maintenance as it becomes older, it is not a priori obvious how time per se and accumulated use separately affects the maintenance costs. Hence, it adds to our understanding of the mechanisms that drives deterioration or a certain maintenance strategy. This is precisely the same analytical challenge as in the analysis of the deterioration of road standard and the relevance of time and use for worsening standards; cf. Nilsson et al. (2015).

The paper is organized as follows. In section 2 we present the methodology we use to estimate the cost impact of rail infrastructure usage. The calculation of our cumulative ton measure is also described. Section 3 contains a description of the relatively long panel of data (16 years) that is available in this paper. The estimation results are presented in section 4. A discussion of the results, together with a conclusion, is given in section 5.

2.0 Methodology

There are two main approaches that can be used in order to establish a relationship between traffic and maintenance costs. One is the bottom-up approach that makes use of engineering models and predicts track damage caused by traffic and then links these damages to costs. See for example Booz Allen Hamilton (2005) and Öberg et al. (2007). The top-down approach on the other hand establishes a direct relationship between traffic and costs using econometric techniques, and has the benefit of putting few restrictions on the elasticities of production.

We consider the econometric (top-down) approach and use a cost function given by equation (1) to derive the cost elasticity with respect to output $\boldsymbol{Q}_{it}$, which is either annual tons or cumulative tons in our model estimations. $\boldsymbol{P}_{it}$ are input prices, $\boldsymbol{F}_{\boldsymbol{it}}$ is a vector of network characteristics, and $\boldsymbol{Z}_{it}$ is a vector of dummy variables. The subscripts $i = 1, 2, \ldots, N$ track sections and $t = 1, 2, \ldots, T$ years of observations.

$$C_{it} = f(\boldsymbol{P}_{it}, \boldsymbol{Q}_{it}, \boldsymbol{F}_{it}, \boldsymbol{Z}_{it}) \qquad (1)$$

The cumulative ton density in each year is expressed as:

$$\sum_{j}^{t} GT_{jit} \qquad (2)$$

where j is the year the track was laid on track section i. We take into account that a track section has segments with varying rail age in the calculation of our cumulative ton measure. These calculations are further described in section 2.1.

A functional form is required in order to estimate the parameters of interest. We choose a logarithmic transformation of the variables (double log functional form) as it can reduce skewness and heteroscedasticity. Moreover, paraphrasing Heij et al. (p. 296, 2004), a logarithmic transformation can be preferred when we believe that agents in maintenance production are more likely to have similar reactions to relative changes compared to changes in absolute levels. We also note that the double log transformation is frequently used in the literature on rail infrastructure maintenance costs (see for example Link et al. 2008 and Wheat and Smith 2008).

We start with the flexible Translog model proposed by Christensen et al. (1971), which is common in analyses of production (see for example Christensen and Greene 1976 for an application to cost functions). More specifically, it is a second order approximation of a production function that puts few restrictions on the elasticities of production, where for example the economies of scale may vary with output levels. We consider A inputs, D outputs, K network characteristics, and M dummy variables, and express the model as

$$\begin{aligned} lnC_{it} = \alpha + \sum_{a=1}^{A} \beta_a lnP_{ait} + \frac{1}{2}\sum_{a=1}^{A}\sum_{b=a}^{A} \beta_{ab}\, lnP_{ait} lnP_{bit} + \sum_{d=1}^{D} \beta_d lnQ_{dit} \\ + \frac{1}{2}\sum_{d=1}^{D}\sum_{e=1}^{E} \beta_{de}\, lnQ_{dit} lnQ_{eit} + \\ \sum_{k=1}^{K} \beta_k lnF_{kit} + \frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{K} \beta_{kl} lnF_{kit} lnF_{lit} + \sum_{a=1}^{A}\sum_{d=1}^{D} \beta_{ad} lnP_{ait} lnQ_{dit} + \\ \sum_{a=1}^{A}\sum_{k=1}^{K} \beta_{rk} lnP_{rit} lnF_{kit} + \sum_{k=1}^{K}\sum_{d=1}^{D} \beta_{kd} lnF_{kit} lnQ_{dit} + \sum_{m=1}^{M} \vartheta_m Z_{mit} + \mu_i + v_{it} \end{aligned} \tag{3}$$

where α is a scalar, μ_i and v_{it} represent unobserved track specific effects and white noise respectively. $\boldsymbol{\beta}$ and $\boldsymbol{\vartheta}$ are vector of parameters to be estimated. We use the following symmetry restrictions: $\beta_{ab} = \beta_{ba}$, $\beta_{de} = \beta_{ed}$, $\beta_{kl} = \beta_{lk}$, $\beta_{ad} = \beta_{da}$, $\beta_{ak} = \beta_{ka}$ and $\beta_{kd} = \beta_{dk}$. A cubic term and quartic for traffic is also included in the model to test for turning points in the cost elasticity with respect to output.

The choice of estimator for our models is largely dependent on the relationship between the unobserved track specific effects (μ_i) and the independent variables. If μ_i is uncorrelated with the independent variables in our model, we prefer the random effects estimator. If this assumption is not valid, the parameter estimates will be biased. We would then prefer the fixed effects estimator which is consistent (however, it is less efficient than the random effects estimator). We use the Hausman test (1978) for this model choice.

2.1 Calculation of cumulative tons

Since the network includes (sections of) rail that were laid as early as around year 1900, it is necessary to have information about traffic since that year in order to calculate the cumulative level of use. However, the level of detail of the available traffic data varies, with data for years 1900-1998 at the national level and 1999-2014 at the track section level. Data at the national level is therefore used to extrapolate tonnage on each track section prior to 1999. In this extrapolation we use the national traffic volumes for years 1900-1998 relative to the national traffic volume of 1999 as weights. Note that we account for variations in the size of the Swedish railway network over the years by using total track length to calculate ton densities (ton-km/track-km) for the entire network. More specifically, for years $t = 1900, \dots, 1998$, the ton density for each section is calculated as

$$Q_{it}^{den} = \frac{\sum_i^N Q_{it}^{den}}{\sum_i^N Q_{i1999}^{den}} Q_{i1999}^{den}, \tag{4}$$

where $i = 1, \dots, N$ track sections and Q^{den} is ton density. $\sum_i^N Q_{it}^{den}$ represents ton density for the entire network. Traffic volumes available at the national level are freight gross ton-km and passenger-km. The former is used when extrapolating freight gross tons and the latter when extrapolating the passenger gross tons. Clearly, passenger-km is not ideal to use in this approximation. However, we are able to calculate a correlation coefficient between passenger-km and ton-km from passenger trains on the Swedish railway network during years 1990 to 2014 (Trafikanalys, 2016). A correlation coefficient at 0.96 indicates that passenger-km is adequate for an approximation of cumulative use in this respect.

The calculation of cumulative tons is made more intricate by the fact that traffic data during 1999 to 2014 do not contain information on the distribution of traffic on parallel tracks at stations; tracks that often were laid in different years and therefore have experienced different levels of cumulative tons. Traffic data and rail age data from 2010 for a few segments of track section 111 in Table 1 is presented as an example. The segment Bln to Bln is part of a station for which there is no traffic data. In this example, there are two tracks at the station Bln. Here it should be noted that a segment may have parts of the track where the rail was inserted in different years, in which case we use the average age in our calculations.

Table 1 – Traffic data and rail data, track section 111 in year 2010

Location from	Location to	Year when rail was inserted	Track no.	Track meters	No. trains
Akt	Bln	2003	-	7 326	10 899
Bln	Bln	2006	1 (main track)	1 641	-
Bln	Bln	2002	2	968	-
Bln	Kå	2006	-	7 270	10 869

We therefore need an assumption of how traffic is distributed between parallel tracks at stations. After a discussion with a rail engineer (Arne Nissen) at the Swedish Transport Administration - the infrastructure manager (IM) - the weights presented in Tables 2 and 3 have been used in the calculations for two parallel tracks at a station.

Table 2 – Single track

Weight	Type of track
1	Single track, line
0.8	Main track, station
0.2	Station track (passing loop)
0.7	Main track, station with platform
0.3	Station track, station with platform (passing loop)

Table 3 – Double track

Weight	Type of track
0.5	Double track, line
0.45	Double track, station
0.1	Double track, station track (passing loop)
0.4	Double track, station with platform
0.2	Double track, station track at station with platform (passing loop)

In the case of more than two parallel tracks at a station, we need to include more weights. Figure 1 is an illustration of how traffic is assumed to be distributed on a station (with a platform) with three parallel tracks.[1] Here we assume that traffic is evenly distributed between the second and third parallel track, which we also do in cases with more than three parallel tracks.

Figure 1 – Illustration of traffic weights for stations with more than two parallel tracks

Descriptive statistics of our cumulative ton measure, along with other variables, is presented in the next section.

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[1] The method with weights is based on the assumption that the number of parallel tracks is the same for the time interval of the rail age between the parallel tracks, which is not necessarily the case. For example, three parallel tracks might historically have been two parallel tracks.

3.0 Data

Information on costs, network characteristics and traffic for the Swedish railway network has been obtained from the IM. As of 2014, there were 244 track sections administered by the IM. We have an unbalanced panel of data for 157 track sections over the period 1999-2014, due to missing data and changes in the number of sections on the railway network. In total, we have access to 2456 observations.

Maintenance cost is the dependent variable in our econometric analysis, and is defined as the cost for activities conducted to maintain the railway's asset. These activities can include minor replacements. Snow removal is currently defined as a maintenance activity, but has been excluded from our main analysis. The reason is that snow removal cost is more related to train density than the deterioration of the tracks that is primarily caused by gross tons.

We test the inclusion of input prices in our analysis, consisting of a proxy for wages and a price index for iron and steel. Information on wages has been collected from the Swedish Mediation Office (via Statistics Sweden) and is the total hourly wage for the occupational category 'building frame and related trade workers', and is available for eight different regions in Sweden.[2] The price index for iron and steel was obtained from Statistics Sweden.

A number of infrastructure characteristics are available from the IM's track information system (BIS). Information on the track length of switches and structures as well as the average age of the rail and of the switches is included in our analysis to account for the heterogeneity in the production environment. We also make use of information on the average quality class (determines the line speed) and the maximum axle load allowed.

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[2] Unfortunately, the occupational categories changed in 2014. We therefore assume that workers in our occupational category have the same percentage change in wages between 2013 and 2014 as workers in the construction industry, for which we have data.

The organization of railway maintenance in Sweden has been reformed during the time period of our data, with the introduction of competitive tendering in 2002. The exposure to competition was gradual, and the last contract tendered in competition started in 2014. To capture the cost impact of tendering we include a dummy variable (CTEND) indicating when a contract area is tendered in competition. Considering that most contracts were not tendered at the beginning of a calendar year, we also include a dummy variable (MIXTEND) indicating the transition from in-house production to tendering. Note that we use year dummies to capture general time related effects not to be confounded with competitive tendering.

Table 4 – Descriptive statistics, 2456 obs. over 1999-2014

Variable	Median	Mean	St. dev.	Min	Max
MAINTC: Maintenance cost, million SEK, incl. snow removal*	9.01	13.42	15.91	0.33	277.52
MAINTCS: Maintenance cost, million SEK, excl. snow removal*	8.29	12.38	14.50	0.32	209.22
WAGE: Hourly wage, SEK*	155.3	156.2	11.9	128.9	187.4
IRON: Iron and steel, price index	111.1	99.3	31.3	52.3	140.9
TON-KM: Million ton-km	195.99	414.57	539.73	0.37	4176.26
TGTDEN: Million total gross ton density**	5.29	8.23	8.71	0.01	65.85
CUMUL.TGTDEN: Million cumulative tons, density**	87.78	129.99	137.30	0.10	844.63
ROUTE_L: Route length, km	46	57	42	2	219
TRACK_L: Track length, km	61	74	52	5	291
RATIO_TLRO: Ratio, track length over route length	1.14	1.56	0.95	1.00	8.08
RAIL_AGE: Rail age, average	19.1	20.1	8.9	2.0	62.0
QUAL_AVE: Quality class, average***	3.1	3.1	1.1	1.0	5.4
SWITCH_L: Switch length, km	1.4	1.8	1.8	0.1	14.4
SWITCH_AGE: Switch age	19.6	20.6	8.7	2.0	48.8
STRUCT_L: Track length of structures (tunnels and bridges), km	0.4	1.2	2.8	0.0	23.2
MAX.AXLE_LOAD: Max. axle load allowed	22.5	23.1	1.7	16.0	30.0
CTEND: Dummy when tendered in competition	0	0.46	0.5	0	1
MIXTEND: Dummy when mix between tend. and not tend.	0	0.06	0.24	0	1

* Costs have been deflated to the 2014 price level using the consumer price index (CPI), ** ton-km/route-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.

In addition to the information presented in Table 4, we need data on traffic and track lengths from years prior to 1999 in order to calculate cumulative tons that different sections have experienced. The age of the rail decides the need of historic information. The IM has provided snapshots of the infrastructure characteristics during each year, from 1999 to 2014. Table 5 shows the track length of newly inserted rails in different decades, and is a snapshot from December 1999. A small share of the rail network had segments with rail inserted in the first decade of the 2000th century. Note that information on rail age is missing for about 9 per cent of the total track length.

Table 5 – Distribution of track lengths and insertion years in 1999

Year when rail inserted	Track length, metres	Share of total track length
1900-1910	14 447	0.1%
1911-1920	31 542	0.3%
1921-1930	139 924	1.2%
1931-1940	284 804	2.3%
1941-1950	233 290	1.9%
1951-1960	834 746	6.9%
1961-1970	1 835 937	15.1%
1971-1980	2 123 456	17.5%
1981-1990	2 774 664	22.9%
1991-1999	3 868 808	31.9%
Total	*12 141 620**	

* The actual total track length is 13 297 919 (including rail with missing data on year inserted)

Information on ton-km and passenger-km during 1900-1998 has been collected from Statistics Sweden, and is presented in Table 10 in appendix, together with track lengths over the same period in Table 11. As noted in section 2.1, we have access to traffic volume at the track section level from 1999 and onwards, while information before 1999 is only available at the national level.

4.0 Results

Two models are estimated, and the results for the first order coefficients are presented in Table 6, while the coefficients for the polynomials and for the cross-products are presented in Tables 7 and 8.[3] Model 1 considers the cumulative ton measure, while Model 2 uses the standard annual ton measure. To take correlation within track sections into account, we use heteroskedastic-robust standard errors. However, there may also be correlation between track sections. Indeed, Pesaran's (2004) test indicates that we have this type of correlation in our dataset (see test results in Table 9). To address the temporal and cross-sectional dependence, we estimate our models with Driscoll and Kraay (1998) standard errors. Moreover, based on the results from the Hausman test, we prefer the fixed effects estimator. All estimations are carried out with Stata 12 (StataCorp.2011).

Before elaborating on the parameter estimates, we note that five outliers were detected. Two track sections had major renewals being made prior to 2013 and 2014, dropping the cumulative ton measure below 1 million and with cost elasticities below -2, and the other three outliers were observations with average costs that were more than 200 times larger than the sample median. These outliers are dropped from the model estimation.

We start with a full Translog model and test down. No interaction and quadratic terms can be dropped from our model based on F-test on linear restrictions, where we test the joint significance of a variable's translog expansion. Hence, the null hypothesis of the Cobb-Douglas restriction is also rejected when testing the joint significance of all the interactions and quadratic terms.

Hourly wages and a price index for iron and steel were tested as input price variables. The price index for iron and steel can only be included as interactions with other variables as it only varies over time and is therefore collinear with the year dummy variables. The

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[3] Note that the first order coefficients can be interpreted as estimates at the sample median as we have transformed all data by dividing by the sample median prior to the log transformation.

parameter estimate for wage was negative in our estimations (yet not significant), and is dropped in the preferred model. Considering this negative result, we prefer not to impose linear homogeneity in input prices by dividing maintenance cost and our price index with wages. We are however able to test if the sum of the interaction terms of the price index variable is zero, a condition required for the linear homogeneity in input prices.[4] Such a restriction could not be rejected in either of the models (F(1, 156)=1.41, Prob>F=0.238 and F(1, 156)=0.36, Prob>F=0.551 in Model 1 and 2, respectively).

The parameter estimates for the characteristics of the infrastructure have the expected signs and are quite similar in both models, except for rail age. The coefficient is -0.2569 (standard error 0.0802) and statistically significant in Model 1, while it is 0.1222 (standard error 0.0503) and significant in Model 2. A difference in these estimates between the models is not very surprising given that rail age (imperfectly) picks up the accumulated use of a track, which is explained by our cumulative ton measure in Model 1. The Model 1 results indicate that rail age alone does not increase maintenance costs, rather the opposite. A reason for a negative coefficient in Model 1 may be that less maintenance is performed on an old track that is going to be renewed within short (see Andersson 2008), while more (preventive) maintenance may be required on renewed tracks in order to uphold their service life. Here it should be noted that we control for that the cost impact of additional tons may vary depending on the age of the tracks. The interaction term between traffic and rail age captures this effect. The coefficient for the interaction between traffic and rail age in Model 2 (TgtdenRail_age) is 0.0862 (with p-value=0.005), showing that cost impact of traffic increases for older tracks. A similar relationship is found for the cumulative ton measure (coefficient is 0.1002), but the estimate is not statistically significant. Clearly, the cost impact of additional tons is higher on

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[4] Other conditions that need to hold are that the sum of the second order terms of the input price variables are zero, as well as the sum of their first order coefficients.

older tracks while rail age alone seems to imply that the IM lowers its expenditure on (preventive) maintenance.

Table 6 – Estimation results (fixed effects), model 1 and model 2

	Model 1 Coef.	Drisc/Kraay Std. Err.	*Model 2* Coef.	Drisc/Kraay Std. Err.
Cons.	15.7822***	0.1225	15.6419***	0.1116
Tgtden	-	-	0.1675***	0.0442
Cumul.tgtden	0.2909***	0.0829	-	-
Track_l	0.7644***	0.1258	0.6791***	0.1336
Ratio_tlro	-0.1449	0.1883	-0.1812	0.1976
Rail_age	-0.2569***	0.0802	0.1222**	0.0503
Qual_ave	-0.0288	0.1818	-0.0473	0.1809
Switch_tl	0.1701***	0.0512	0.0973	0.0766
Switch_age	0.1299***	0.0464	0.0954*	0.0519
Struct_tl	0.0913**	0.0400	0.1048**	0.0406
Max.axle_load	0.4826	0.4060	0.5222	0.4026
Year00	-0.0059	0.0173	-0.0030	0.0195
Year01	0.0074	0.0202	0.0200	0.0222
Year02	0.1956***	0.0255	0.2154***	0.0274
Year03	0.1590***	0.0321	0.1831***	0.0347
Year04	0.2136***	0.0354	0.2338***	0.0378
Year05	0.2150***	0.0448	0.2411***	0.0457
Year06	0.1312**	0.0537	0.1631***	0.0531
Year07	0.1967***	0.0600	0.2255***	0.0606
Year08	0.2394***	0.0631	0.2711***	0.0635
Year09	0.3260***	0.0628	0.3677***	0.0628
Year10	0.2469***	0.0670	0.2868***	0.0660
Year11	0.3707***	0.0686	0.4204***	0.0682
Year12	0.4073***	0.0683	0.4658***	0.0668
Year13	0.5356***	0.0672	0.6037***	0.0656
Year14	0.7061***	0.0635	0.7786***	0.0632
Mixtend	-0.0294	0.0261	-0.0249	0.0288
Ctend	-0.1217***	0.0385	-0.1233***	0.0404
No. Obs.	2541		2541	

We have transformed all data by dividing by the sample median prior to taking logs. Hence, the first order coefficients can be taken as cost elasticities at the sample median.

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

Table 7 – Estimation results (fixed effects), model 1 and model 2, cont.

	Model 1 Coef.	Drisc/Kraay Std. Err.	*Model 2* Coef.	Drisc/Kraay Std. Err.
Tgtden^2	-	-	0.0299	0.0402
TgtdenIron	-	-	0.0297	0.0303
TgtdenTrack_l	-	-	-0.0411**	0.0192
TgtdenRatio_tlro	-	-	-0.0540	0.0477
TgtdenRail_age	-	-	0.0862***	0.0300
TgtdenQual_ave	-	-	0.2113**	0.1050
TgtdenSwitch_tl	-	-	0.0232	0.0248
TgtdenSwitch_age	-	-	-0.0238	0.0411
Tgtden_Struct_tl	-	-	0.0133	0.0212
TgtdenMax.axle_load	-	-	-0.2677	0.1871
Cumul.tgtden^2	-0.0877	0.0584	-	-
Cumul.tgtden^3	0.1636***	0.0514	-	-
Cumul.tgtden^4	0.1605***	0.0615	-	-
Cumul.tgtdenIron	0.0354	0.0282	-	-
Cumul.tgtdenTrack_l	0.0949*	0.0503	-	-
Cumul.tgtdenRatio_tlro	-0.0325	0.0876	-	-
Cumul.tgtdenRail_age	0.1002	0.0720	-	-
Cumul.tgtdenQual_ave	0.2395	0.1461	-	-
Cumul.tgtdenSwitch_tl	0.1345***	0.0377	-	-
Cumul.tgtdenSwitch_age	0.0291	0.0540	-	-
Cumul.tgtdenStruct_tl	-0.0268	0.0340	-	-
Cumul.tgtdenMax.axle_load	-0.2689	0.1931	-	-
IronTrack_l	-0.0384	0.0485	-0.0018	0.0467
IronRatio_tlro	0.0482	0.0655	0.1108	0.0750
IronRail_age	-0.0468	0.0665	-0.0090	0.0700
IronQual_ave	0.1880	0.1176	0.2030*	0.1159
IronSwitch_tl	-0.0529	0.0321	-0.0478	0.0395
IronSwitch_age	-0.0316	0.0754	-0.0448	0.0598
IronStruct_tl	0.1026**	0.0452	0.0874**	0.0431
IronMax.axle_load	-0.7326**	0.3598	-0.6388	0.4044
Track_l^2	0.6018***	0.1699	0.4988***	0.1219
Track_lRatio_tlro	-0.2124	0.2579	-0.2019	0.2528
Track_lRail_age	0.0693	0.0656	0.1537***	0.0540

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

Table 8 – Estimation results (fixed effects), model 1 and model 2, cont.

	Model 1	Drisc/Kraay	*Model 2*	Drisc/Kraay
	Coef.	Std. Err.	Coef.	Std. Err.
Track_lQual_ave	-0.3602*	0.1880	-0.5217***	0.1684
Track_lSwitch_tl	0.1255**	0.0525	0.1603***	0.0312
Track_lSwitch_age	-0.0170	0.0742	-0.0370	0.0761
Track_lStruct_tl	-0.0282	0.0303	-0.0287	0.0351
Track_lMax.axle_load	-0.4539	0.3685	-0.3771	0.3173
Ratio_tlro^2	-0.0803	0.2207	-0.0924	0.2199
Ratio_tlroRail_age	0.2072**	0.0829	0.1453	0.1033
Ratio_tlroQual_ave	-0.5201*	0.3015	-0.5308*	0.2714
Ratio_tlroSwitch_tl	-0.0718	0.0936	0.0794	0.0590
Ratio_tlroSwitch_age	0.0557	0.0964	0.0805	0.1121
Ratio_tlroStruct_tl	-0.0082	0.0767	-0.0514	0.0607
Ratio_tlroMax.axle_load	-0.6357	0.9171	-0.5658	0.8703
Rail_age^2	-0.0094	0.0861	0.1158	0.0914
Rail_ageQual_ave	-0.2044	0.2217	0.1399	0.1699
Rail_ageSwitch_tl	-0.1986***	0.0505	-0.1003**	0.0480
Rail_ageSwitch_age	0.1070	0.0760	0.1336**	0.0635
Rail_ageStruct_tl	-0.0569	0.0616	-0.0481	0.0626
Rail_ageMax.axle_load	1.6186***	0.5116	0.9882*	0.5046
Qual_ave^2	0.1053	0.5683	0.2628	0.3844
Qual_aveSwitch_tl	0.0080	0.1453	-0.1069	0.1291
Qual_ageSwitch_age	0.0453	0.1294	-0.0181	0.1167
Qual_aveStruct_tl	0.1912	0.0592	0.2865***	0.0672
Qual_aveMax.axle_load	-0.7218	0.8109	-0.7423	0.8957
Switch_tl^2	0.0266	0.0396	0.0170	0.0557
Switch_tlSwitch_age	-0.0610	0.0433	-0.0370	0.0396
Switch_tlStruct_tl	-0.1083***	0.0310	-0.1018***	0.0317
Switch_tlMax.axle_load	0.0023	0.3367	0.0627	0.3114
Switch_age^2	-0.0804	0.1313	-0.0561	0.1296
Switch_ageStruct_tl	-0.0145	0.0305	-0.0263	0.0306
Switch_ageMax.axle_load	-1.6752*	0.8833	-1.4458*	0.8422
Struct_tl^2	0.0292	0.0302	0.0288	0.0357
StructMax.axle_load	-0.2357	0.2245	-0.3277	0.2133
Max.axle_load2	2.7390	2.1666	1.1466	1.7327

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

Table 9 - Test statistics

	Model 1		*Model 2*	
Pesaran's test[5]	-2.063	P-value=0.039	-2.093	P-value=0.036
Hausman's test statistic[6,7]	Chi2(64)=174.95	P-value=0.000	Chi2(64)=128.96	P-value=0.000
Test of Cobb-Douglas restriction	F(15, 156)=60.57	P-value=0.000	F(15, 156)=95.74	P-value=0.000
Mean Variance Inflation Factor	8.15		6.85	

The organisational reform initiated in 2002 had an effect on maintenance costs. Specifically, competitive tendering reduced costs with about 11 to 12 per cent according to the estimation results[8], which is similar to previous results on the Swedish reform using data over the period 1999-2011 (see Odolinski and Smith 2016). Here it should be noted that the exposure to competition was gradual, which means that there are no general pre- and post-competitive tendering periods in our dataset. Hence, the year dummy variables are used to control for general time effects not to be confounded with the effects of tendering. Moreover, a general difference-in-differences approach would also include a dummy variable indicating whether a track section belongs to a contract area tendered in competition sometime during the period in our study. However, considering that the last contract area was tendered in competition in 2014, this type of dummy is not (and cannot be) considered in the estimations.

The coefficients for traffic in both models are the parameters of main interest in this study. The first order coefficients are both positive and significant. Moreover, we cannot reject the joint significance of the second, third and fourth order coefficients for cumulative tons, showing that there is a quartic relationship between maintenance costs and traffic in Model 1. A similar relationship could not be found for annual tons; however, the joint significance of the squared term and its interaction terms could not be rejected.

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[5] Test is made on a balanced panel of 2144 obs. The null hypothesis is cross sectional independence.

[6] We exclude year dummy variables in the test (see Imbens and Wooldridge 2007).

[7] The covariance matrices in the test are based on the disturbance estimates from the fixed effects estimator.

[8] The coefficients (CTEND) are -0.1217 and -0.1233 in Model 1 and 2 respectively, which translates in to exp(-0.1217)-1=-0.1146 per cent and exp(-0.1233)-1=-0.1160 per cent cost reductions.

Importantly, the cost elasticity with respect to cumulative tons (evaluated at the sample median) is larger than the annual ton cost elasticity. The difference between these estimates is however not statistically different from zero (see Cohen et al. 2003, p. 46-47, for formulas on standard errors of the difference between estimates from different regressions).

For graphical evaluation of the quartic relationship between traffic and costs in Model 1, we present the cost elasticities with respect to cumulative tons in Figure 2, evaluated at the sample median of the interaction terms. An initial sharp increase in cost elasticity is found for the cumulative ton measure, suggesting that (preventive) maintenance is quite reactive to traffic on recently renewed (or built) tracks. Such a maintenance strategy may be the reason for the turning point, indicating a fall with a decreasing rate, which suggests that less (corrective) maintenance is required on tracks that are probably in a relatively good shape. The decrease in the cost elasticity is followed by yet another turning point, showing that a heavily used track will eventually require more maintenance in order to maintain a certain service level.

Indeed, the cost elasticity increases to quite high levels when the tracks have been extensively used. The expected annual maintenance costs of letting a track section experience yet another million tonnes of traffic will eventually be higher than the expected (annual) renewal cost. Hence, this increase in maintenance costs is partly what motivates a renewal.

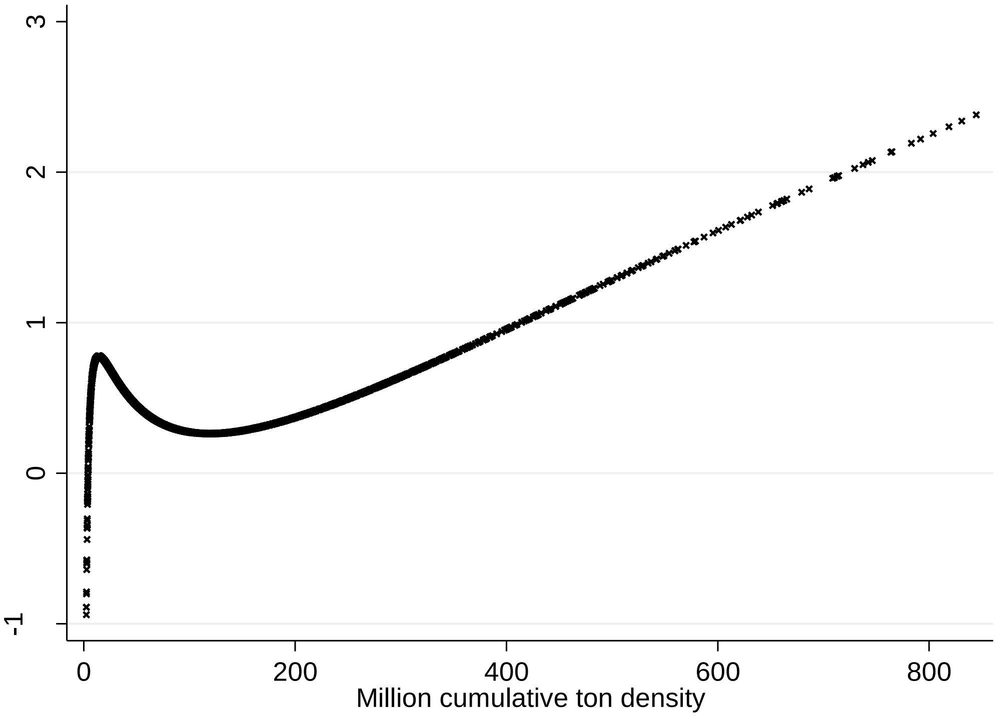

Figure 2 – Cost elasticities with respect to cumulative tons (evaluated at the sample median of infrastructure characteristics)

5.0 Discussion and conclusion

In this paper we have estimated the impact of accumulated rail infrastructure use on maintenance costs. A comparison with the effect of annual tons is made, showing that the cost elasticity is higher for the cumulative ton measure. The new traffic measure also allows us to shed new light on how maintenance costs vary with the age of the tracks. It is clear that a rail age variable does not only pick up the effect of past use when estimating the cost impact of annual tons on the railway network. The estimate goes from positive in the model with annual tons, to negative in the model with cumulative tons. This implies that when rail age is not associated with past (or current) use, it can instead point out tracks that that the IM does not (currently) prioritize in its maintenance activities. Moreover, the estimations also generate the intuitive result that the cost impact of traffic is higher when the tracks are older, as indicated by the interaction term between traffic and rail age.

Furthermore, the results in this paper can be an important input in the IM's maintenance strategy, which needs to consider whether to continue spending resources on maintenance activities or renew the tracks. More specifically, we have shown that the estimated cost elasticities with respect to cumulative tons are rather high when the tracks have been extensively used since they were originally laid. Eventually, the expected cost of annual maintenance will be higher than the expected annual renewal cost.

It should be noted that the cumulative measure in this paper is an approximation of the accumulated use of the Swedish railway network. However, we have used detailed information on rail age and traffic in the extrapolation of traffic in years prior to 1999, which in the end generated reasonable and intuitive estimation results.

Future research can make use of the cumulative measure in order to study the relationship between traffic and track related failures. This knowledge can further be used to determine the appropriate time for the renewal of a track, where both producer and user costs (stemming from track related failures) are taken into account. The (producer and user) cost impact of cumulative use will be the main factor for the timing of a track renewal. Moreover, future research could also consider cumulative use from a marginal cost perspective; is there reason to include accumulated use in track access charges imposed on train operators in Europe? From one perspective, this marginal cost is closer to the actual maintenance cost caused by an extra ton on the tracks that are currently in place, compared to a model that uses an annual ton measure which disentangles the effect of past traffic from the short-run marginal cost. On the other hand, one can argue that an operator should not pay for past traffic levels. Still, the inclusion of past traffic does not necessarily need to imply double counting; the cost elasticity with respect to cumulative use can be multiplied with the average cost per ton-km per year. In that way, one can account for the heterogeneity of the rail infrastructure standard - as measured by cumulative use - in the estimation of the model, and still calculate short-run marginal costs per ton-km.

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Appendix

Table 10 - Million ton-km and passenger-km, 1900-1998

Year	*Ton-km*	*Pass.-km*
1900	1 459	823
1901*	1 672	979
1902*	1 672	979
1903	1 713	968
1904	1 820	1 045
1905	1 887	1 099
1906	2 071	1 263
1907	2 192	1 414
1908	2 140	1 443
1909	1 981	1 465
1910	2 462	1 576
1911	2 611	1 638
1912	2 890	1 730
1913	3 164	1 849
1914	3 107	2 012
1915	4 391	2 147
1916	5 309	2 409
1917	4 537	2 402
1918	3 992	2 244
1919	3 123	2 451
1920	3 268	2 409
1921	2 350	2 163
1922	2 714	2 047
1923	2 856	2 047
1924	3 166	2 010
1925	3 424	2 039
1926	3 554	2 095
1927	3 909	2 167
1928	3 103	2 222
1929	4 557	2 295
1930	4 228	2 436
1931	3 461	2 324
1932	2 504	2 262
1933	2 525	2 268
1934	3 354	2 480
1935	3 890	2 702
1936	4 549	2 890
1937	5 614	3 102
1938	5 212	3 261
1939	6 060	3 565
1940	7 216	4 495
1941	7 976	5 023
1942	8 477	5 743
1943	8 818	6 384
1944	8 121	6 580
1945	6 996	6 441
1946	8 088	6 405
1947	8 127	6 515
1948	8 459	6 579
1949	8 107	6 725
1950	8 640	6 637
1951	10 027	6 508
1952	9 633	6 333
1953	9 017	6 234
1954	9 235	6 138
1955	10 320	6 163
1956	10 969	6 237
1957	10 396	5 642
1958	9 475	5 312
1959	9 685	5 052
1960	10 928	5 180
1961	11 100	5 310
1962	11 064	5 353
1963	12 015	5 237
1964	12 919	5 371
1965	13 883	5 344
1966	14 062	5 133
1967	13 538	4 806
1968	14 798	4 603
1969	16 021	4 792
1970	17 311	4 640
1971	15 658	4 025
1972	16 214	4 533
1973	18 260	4 645
1974	19 598	5 480
1975	16 057	5 615
1976	16 238	5 617
1977	14 782	5 563
1978	14 764	5 557
1979	17 347	6 224
1980	16 648	6 998
1981	15 410	7 062
1982	14 331	6 695
1983	15 445	6 776
1984	17 776	6 797
1985	18 420	6 911
1986	18 553	6 571
1987	18 406	6 433
1988	18 687	6 669
1989	19 137	6 647
1990	19 102	6 600
1991	18 816	5 985
1992	19 202	5 963
1993	18 578	6 422
1994	19 069	6 507
1995	19 391	6 833
1996	18 846	6 953
1997	19 181	7 022
1998	19 163	7 210

Table 11 – Track lengths, 1900-1998

Year	Track length, km	**Year**	Track length, km	**Year**	Track length, km
1900	11 303	**1933**	16 812	**1966**	13 067
1901	11 573	**1934**	16 824	**1967**	12 907
1902	11 950	**1935**	16 772	**1968**	12 162
1903	12 289	**1936**	16 709	**1969**	11 920
1904	12 543	**1937**	16 883	**1970**	11 780
1905	12 647	**1938**	16 886	**1971**	11 748
1906	13 088	**1939**	16 757	**1972**	11 680
1907	13 248	**1940**	16 756	**1973**	11 680
1908	13 364	**1941**	16 581	**1974**	11 679
1909	13 604	**1942**	16 583	**1975**	11 690
1910	13 829	**1943**	16 567	**1976**	11 690
1911	13 942	**1944**	16 569	**1977**	11 706
1912	14 171	**1945**	16 552	**1978**	11 703
1913	14 377	**1946**	16 552	**1979**	11 635
1914	14 644	**1947**	16 552	**1980**	11 635
1915	14 863	**1948**	16 528	**1981**	11 593
1916	14 971	**1949**	16 533	**1982**	11 864
1917	15 031	**1950**	16 516	**1983**	11 821
1918	14 852	**1951**	16 599	**1984**	11 784
1919	15 154	**1952**	16 583	**1985**	11 466
1920	15 160	**1953**	16 456	**1986**	11 473
1921	15 186	**1954**	16 396	**1987**	11 491
1922	15 401	**1955**	16 194	**1988**	11 410
1923	15 502	**1956**	16 085	**1989**	11 339
1924	15 710	**1957**	15 915	**1990**	11 118
1925	15 981	**1958**	15 840	**1991**	10 985
1926	16 079	**1959**	15 611	**1992**	10 923
1927	16 271	**1960**	15 219	**1993**	10 823
1928	16 701	**1961**	14 794	**1994**	10 738
1929	16 722	**1962**	14 254	**1995**	10 859
1930	16 810	**1963**	14 063	**1996**	10 898
1931	16 770	**1964**	13 721	**1997**	10 875
1932	16 776	**1965**	13 433	**1998**	10 932