Railway line capacity utilisation and its impact on maintenance costs

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Keywords: maintenance, marginal cost, rail infrastructure, capacity, track access charges

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Abstract

In this paper, we analyse how railway maintenance costs are affected by different levels of railway line capacity utilisation. Previous studies have focused on the wear and tear of the infrastructure, while this paper shows that it is important to also acknowledge the heterogeneity of the maintenance production environment. Specifically, we estimate marginal costs for traffic using econometric methods on a panel dataset from Sweden and show that these costs increase with line capacity utilisation. The results are significant considering that current EU regulation (2015/909) states that track access charges can be based on marginal costs, with the aim of creating an effective use of available infrastructure capacity.

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1. Introduction

The use of track access charges has become a requirement within the European Union after the vertical separation between infrastructure management and train operations. It is established in the EU regulation 2015/909 that these charges should be based on the direct cost to the infrastructure manager of running a vehicle on the tracks. One part of these costs concerns the maintenance performed due to wear and tear of the rail infrastructure. The overall weight of rolling stock is an important cost driver in this aspect, and hence, gross ton-km is a rather common charging unit among infrastructure managers in Europe.

There are other aspects that are also important for explaining the maintenance cost level. Different characteristics of the infrastructure such as the age and structure of the track, curvature, the number of switches and line speed are important cost drivers (see for example Öberg et al. (2007) and Odolinski and Nilsson (2017)), as well as vehicle and running gear characteristics, such as wheel slip, unsprung mass and curving performance (see Boysen and Andersson (1989)). These characteristics are often used as control variables in econometric studies that attempt to establish a relationship between traffic and costs (except the vehicle characteristics which can be used to differentiate the marginal costs; see Booz Allen Hamilton (2005), Öberg et al. (2007), and Smith et al. (2017)). Capacity utilisation is however a factor that has not been fully recognised in studies on marginal maintenance costs of rail infrastructure use.

The purpose of this paper is to estimate cost elasticities with respect to traffic that may capture potential differences in maintenance costs with respect to line capacity utilisation. These elasticities can be used to differentiate marginal maintenance costs. If these costs vary for different levels of capacity utilisation, then track access charges should be set accordingly in order to create a more efficient use of the infrastructure, according to the short-run marginal cost pricing principle.[1]

The literature on the marginal maintenance costs for rail infrastructure use has focused on the wear and tear caused by traffic (see for example Munduch et al. (2002), Johansson and Nilsson (2004), Öberg et al. (2007), Andersson (2008), Link et al. (2008), Wheat et al. (2009), Odolinski and Nilsson (2017)). From an engineering perspective, the wear and tear (need of repair) of the infrastructure may be non-linear with respect to traffic – that is, a proportional increase in traffic may result in disproportionate increases in wear and tear depending on the traffic level and the contributing damage mechanisms. For example, Öberg et al. (2007) find a non-linear relationship between axle load and track deterioration, while examples of studies that find a non-linear relationship between traffic and costs are Wheat and Smith (2008), Marti et al. (2009), Andersson (2011) and Odolinski (2016).

From a production perspective, different levels of traffic will also create different possibilities to maintain the assets. This effect is dependent on the line capacity utilisation. For example, if the available infrastructure capacity is heavily used, i.e. the line capacity usage is high, then the time slots for maintenance activities may be short and fragmented which creates more interruptions of the maintenance work, and/or maintenance activities need to be performed at night, which tends to be more costly. Indeed, according to Lidén and Joborn (2016), the planning regime for maintenance in Sweden lets the maintenance contractors apply for slots at a late stage in the planning process, which makes it difficult to find possessions that are cost efficient (with respect

[1] There are situations in which it is relevant to deviate from the marginal cost, see for example Rothengatter (2003). Still, as argued by Nash (2003), this does not change the fact that marginal cost should be the basis for an efficient pricing policy.

to maintenance production costs). In other words, traffic and infrastructure design with respect to capacity have an impact on scheduling track possession. Moreover, considering that tracks with high capacity utilisation are more sensitive to delays (Lindfeldt (2015)), where disruptions can result in significant user costs, there is reason to carry out more (preventive) maintenance when capacity utilisation increases. The aim of this paper is therefore to study if and how capacity utilisation affects maintenance costs.

It can be noted that several European countries have track access charges that are differentiated with respect to line capacity utilisation. For example, in the United Kingdom, these charges are used to recover the delay costs incurred on the infrastructure manager (Network Rail) by increased traffic, a charge that is based on the relationship between line capacity utilisation and 'congestion related reactionary delay' (Rail Delivery Group (2014)). The Swedish infrastructure manager (Trafikverket, hereafter referred to as the IM) also uses a capacity charge, stating that the aim is to create a more efficient use of railway capacity. However, the charges in Sweden have not been based on empirical evidence on how capacity utilisation affects maintenance costs.

This paper is organized as follows. Section 2 gives and overview of railway infrastructure capacity and its relationship with maintenance. This forms the basis for the infrastructure capacity variables that will be used in the estimation approach, which is presented in section 3. The model we estimate is presented in subsection 3.1, while the calculation of marginal costs for traffic is described in subsection 3.2. Descriptive statistics of the data used in the estimations are provided in section 4. Estimation results are presented in section 5, and section 6 concludes.

2. Railway infrastructure capacity and maintenance

For railways, there is a theoretical capacity that corresponds to a certain number of passengers or net cargo that can be transported past a point of the infrastructure (line or junction) during a certain time period. This measure is the product of train capacity (passengers or tons per train) and line capacity (trains per time period). In this paper, we are interested in line capacity and its level of usage. When analysing the line capacity, the UIC (2013) states that one first and foremost needs a definition of the infrastructure and timetable boundaries (which should be interlocked). The next step is to calculate the capacity use, which is defined as "…the utilisation of an infrastructure's physical attributes along a given section, measured over a defined time period." (UIC 2013, p. 13).[2] The Swedish IM bases its capacity calculations on the UIC leaflet, and uses 6 hours per day as the additional time to secure quality of operation in the calculations, which include track possession for maintenance activities.

The additional times used for maintenance are in reality heterogeneous. First of all, track possession times depend on the work to be performed, which may require possession times from one hour (or less) to several days. For example, signal repair, snow removal, and tamping of turnouts can take 1 to 4 hours, grinding and tamping of tracks can take 4 to 8 hours, while urgent repair may take several days (see Lidén (2014) for a list of maintenance activities with different time possessions and planning horizons). The required possession times, together with the planning horizon for maintenance and the planning process for obtaining possessions, will thus to a large extent determine the possession times given to maintenance production.

Nilsson et al. (2015) describe the planning process in Sweden and the priority setting used: The maintenance (and renewal)[3] activities that have a long planning horizon and require exclusive and long consecutive track possessions in which the track is closed for traffic, are determined at an early stage in the timetabling process. In fact, these activities are planned before the train operators

[2] Specifically, the percentage capacity consumption is defined as $\frac{Occupancy\ time + Additional\ times}{Defined\ time\ period} \cdot 100$, where "additional times" is set (by the infrastructure manager) in order to secure quality of operation.

[3] Note however that renewals are not considered in this study.

can make requests on train paths. Track possessions for the other maintenance activities, with shorter planning horizons, are determined simultaneously with the train operators' requests for train paths. When there is a conflict between requests for track possessions, the IM uses a set of priority criteria with the aim of finding the solution with the highest socio-economic benefit. The priority criteria are presented in the annual network statement by the Swedish IM (see for example Trafikverket (2015)). Requests for possession times for maintenance are in this case treated by calculating the alternative production costs for other possession times than those requested (the Swedish IM are however aware that the solution is complex, and that the model and priority criteria used is not optimal)[4]. When the timetable has been set, there are (often) free time slots. Train operators and maintenance contractors can apply for these slots, where the main principle is 'first come, first served'. The length of time slots varies depending on the capacity utilisation. Nilsson et al. (2015) provide an example from a maintenance contract, where four different sections of the track had different time slots available. One section had 5 consecutive hours, with one track open for traffic, while the other sections had between 2 and 6 consecutive hours with no other traffic running.

Clearly, the maintenance production environment is heterogeneous, where the track possession times available for maintenance can vary considerably between different track sections. Specifically, the timetabling process described above is interconnected to the infrastructure design and the traffic demand. As described in UIC (2013), Nelldal et al. (2009), and Boysen (2013), other

[4] See for example Brännlund et al. (1998), who presents an optimization approach for finding a profit maximizing timetable with respect to track capacity constraints, which now has resulted in attempts to develop an optimization tool for timetabling (Nilsson et al. 2017). See also Lusby et al. (2011) for a survey of models and methods for railway track allocation, and Lidén (2016) for a treatment of the planning and scheduling problem for maintenance in coordination with traffic.

important factors for the level of capacity available in railway systems are the number of tracks, the signalling system, the distances between passing sidings, interlockings (such as stations, nodes and junctions), train speeds and train speed heterogeneity. The interaction between these factors determines the production environment for maintenance and its track possessions. In this study, we consider some of these factors in the assessment of whether and how line capacity utilisation has an impact on maintenance costs.

3. Estimation approach

The marginal cost pricing principle is the basis for the analysis in this paper, which means that the short-run marginal cost of infrastructure use is estimated. From a wear and tear perspective, gross ton-km (GTKM) is a relevant charging unit, and hence, the marginal cost (MC) is derived as (see Munduch et al. (2002) or Odolinski and Nilsson (2017)):

$$MC_{it} = \frac{\partial C_{it}}{\partial GTKM_{it}} = \frac{GTKM_{it}}{C_{it}} \frac{\partial C_{it}}{\partial GTKM_{it}} \frac{C_{it}}{GTKM_{it}} = \frac{\partial lnC_{it}}{\partial lnGT_{it}} \frac{C_{it}}{GTKM_{it}}, \tag{1}$$

where C_{it} is maintenance costs on track section i in year t. Specifically, the cost elasticity with respect to gross tons ($\frac{\partial lnC_{it}}{\partial lnGT_{it}}$) needs to be derived and multiplied with the average cost ($\frac{C_{it}}{GTKM_{it}}$). From a line capacity usage perspective, train-km (TKM) may also be a relevant charging unit. Therefore, this measure is also considered in the marginal cost estimations – that is, we also estimate $\frac{\partial C_{it}}{\partial TKM_{it}}$.

The main approaches used in previous research to estimate the marginal cost of infrastructure use are the so-called bottom-up approaches (see Booz Allen Hamilton (2005) and Öberg et al. (2007)) and top-down approaches (see for example Munduch et al. (2002), Johansson and Nilsson (2004), Link et al. (2008) and Wheat et al. (2009)). The former approach uses engineering models to establish a relationship between traffic and wear and tear of the infrastructure, and then links costs to the damage measures, whereas the latter establishes a direct relationship between costs and traffic. The bottom-up approach is good at describing the infrastructure damage mechanisms caused by traffic (e.g. rolling contact fatigue, abrasive wear, track settlement and component fatigue), while the top-down approach is good at linking different cost drivers (such as traffic) to actual costs, allowing for various elasticities of production (depending on the cost function that is specified).

We use the econometric top-down approach, considering that the aim of this paper is to establish a relationship between maintenance costs and the traffic volume's interaction with line capacity. This implies that the cost impact of line capacity utilisation needs to be considered in this estimation, and the marginal cost charges need to be differentiated accordingly (the specification of our model in section 3.1 below reveals how this is achieved).

As previously noted, there are different factors that determine the level of capacity that is available in the railway system, such as the number of tracks, the signalling system, the distances between passing sidings, interlockings, train speeds and train speed heterogeneity and how the timetable is constructed. The factors considered in this study are infrastructure characteristics and traffic volume. Specifically, we use data from the Swedish IM's track information system 'BIS' and create two different variables for infrastructure capacity:

- Track length/Route length (average number of tracks), and
- Number of passing sidings per route-km

Note that track length only includes the main tracks, i.e. yard tracks are not included (which may be used for storage and thus do not have an impact on line capacity). The definition of passing sidings follows the definition provided in Lindfeldt (2009, pp. 13-14). For single tracks, there should be more than one track on a station in order to be defined as a passing siding. For double tracks, there should be more than two tracks, where at least one of the tracks is not classified as main track.

The traffic variables we use are the number of gross tons and the number of trains that have run on a track section during a year. Regarding the impact of train speeds, we have information about the quality class number on a track section, which indicates the maximum speed allowed (higher speeds generally imply more trains per time period, yet this depends on the signalling system; see Nelldal et al. (2009)). However, its impact on capacity can be difficult to isolate from the effect line speed has on the wear and tear of the infrastructure, as well as from effects caused by differences in requirements on track geometry standard. Considering train speed heterogeneity, we do have information on whether the train is a passenger or a freight train. We can therefore (to some extent) capture the effect of traffic homogeneity with respect to speeds. We define these variables as $\left|\frac{\text{Passenger gross ton-km}}{\text{Total gross ton-km}} - 0.5\right|$, and $\left|\frac{\text{Passenger train-km}}{\text{Total train-km}} - 0.5\right|$, which thus can take a value on the interval [0, 0.5], where 0 implies a 50-50 mix between passenger and freight traffic, while 0.5 implies that either passenger or freight traffic is the only traffic type on the railway line (i.e. homogeneous traffic).

We consider the timetabling process to be relatively fixed, where any changes over time are due to changes in traffic demand and/or changes in infrastructure characteristics. If this is not the case, i.e. if the timetabling process changes due to factors not captured by our explanatory variables, we might have a problem with omitted variable bias. However, if these are general effects over the railway network, then they can be captured by year dummy variables (the specification of the model is presented below).

3.1 Model

To derive the cost elasticity with respect to traffic and capacity, we use a short run cost function

$$C_{it} = f(Q_{it}, \sum_{k=1}^{3} K_{kit}, \sum_{l=1}^{L} X_{lit}, \sum_{m=1}^{M} Z_{mit}), \tag{2}$$

where C_{it} is maintenance costs in track section i during year t. Q_{it} is the traffic volume (gross tons or trains), and $\sum_{k=1}^{3} K_{kit}$ is our set of infrastructure capacity measures: track length/route length, number of passing sidings per route-km, and train speed homogeneity ($|\frac{\text{Passenger gross ton-km}}{\text{Total gross ton-km}} - 0.5|$, or $|\frac{\text{Passenger train-km}}{\text{Total train-km}} - 0.5|$). $\sum_{l=1}^{L} X_{lit}$ are other network characteristics such as track length and quality class (linked to line speed). $\sum_{m=1}^{M} Z_{mit}$ are dummy variables.

To capture the effect of capacity utilisation in the estimation of marginal costs, we need to consider the interaction between traffic and infrastructure capacity (K_{it}), as well as non-linear effects of traffic. A flexible model that includes these types of effects is the Translog model, which was proposed by Christensen et al. (1971). It is a second order approximation of a cost (production) function (see Christensen and Greene (1976) for an application to cost functions). The cost model we estimate is

$$lnC_{it} = \alpha + \beta_0 lnC_{it-1} + \beta_m lnQ_{mit} + \frac{1}{2}\beta_{mn} lnQ_{mit} lnQ_{nit} + \beta_k lnK_{kit} + \frac{1}{2}\beta_{kp} lnK_{kit} lnK_{pit} + \beta_{km} lnK_{kit} lnQ_{mit} + \sum_{l=1}^{L} \beta_l lnX_{lit} + \frac{1}{2}\sum_{l=1}^{L}\sum_{r=1}^{L} \beta_{lr} lnX_{lit} lnX_{rit} + \sum_{l=1}^{L} \beta_{lm} lnX_{lit} lnQ_{mit} + \sum_{l=1}^{L} \beta_{lk} lnX_{lit} lnK_{kit} + \sum_{d=1}^{D} \vartheta_d Z_{dit} + \mu_i + v_{it}, \tag{3}$$

where α is a scalar, v_{it} the error term, and μ_i is the impact of unobserved track section specific effects. β_m, β_{mn}, β_k, β_{kp}, β_{km}, β_l, β_{lr}, β_{lm}, β_{lk}, and ϑ_d are parameters to be estimated (the symmetry restrictions $\beta_{mn} = \beta_{nm}$, $\beta_{kp} = \beta_{pk}$, $\beta_{km} = \beta_{mk}$, $\beta_{lr} = \beta_{rl}$, $\beta_{lm} = \beta_{ml}$, $\beta_{lk} = \beta_{kl}$ are used). The Cobb-Douglas constraint $\beta_{mn} = \beta_{kp} = \beta_{km} = \beta_{lr} = \beta_{lm} = \beta_{lk} = 0$ is tested using and F-test. We use a double-log specification as our functional form, which can reduce heteroscedasticity and skewness (Heij et al. (2004)). This functional form is common in the literature on rail infrastructure costs (see for example Munduch et al. (2002), Link et al. (2008), Wheat and Smith (2008), Odolinski and Nilsson (2017), Odolinski and Wheat (2018)).

We also include lagged maintenance costs (lnC_{it-1}) in the model to capture dynamic effects in the maintenance production; a change in a cost driver (such as traffic) during a year might also have an impact on costs in the subsequent year(s). This effect was for example found by Andersson (2008), Odolinski and Nilsson (2017), and Odolinski and Wheat (2018). The lagged maintenance costs lnC_{it-1} are however correlated with the (time-invariant) individual effects μ_i. We use the forward orthogonal deviation to remove these track section specific effects, a transformation proposed by Arellano and Bover (1995). Moreover, lagged maintenance costs are correlated with the error terms v_{it}. We therefore use instruments for the lagged variables. The best instruments available to us are further lags of the lagged variable(s) (which are not correlated with the error terms v_{it}), where a longer set of lags can improve estimation efficiency. To not lose observations when increasing the number of lags, we use the method by Holtz-Eakin et al. (1988) in which missing values are substituted by zeros.

The estimates $\hat{\beta}_k$ and $\hat{\beta}_{kp}$ comprise the effects our infrastructure capacity measure has on costs, while $\hat{\beta}_m$ and $\hat{\beta}_{mn}$ capture the impact traffic has on costs. Moreover, the estimate $\hat{\beta}_{km}$

captures the cost impact of an increase in traffic when the level of infrastructure capacity increases – that is, it allows us to evaluate the cost elasticity for traffic with respect to different levels of infrastructure capacity, while holding the other variables constant. More specifically, the effect of a change in traffic is

$$\frac{\partial lnC_{it}}{\partial lnQ_{it}} = \hat{\beta}_m + \hat{\beta}_{mn} lnQ_{it} + \hat{\beta}_{km} lnK_{it}, \tag{4}$$

We test the inclusion of interaction terms between the squared capacity and traffic variables – that is, we include $\frac{1}{2}\beta_{kpm} lnK_{kit} lnK_{pit} lnQ_{mit}$ and $\frac{1}{2}\beta_{mnk} lnQ_{mit} lnQ_{nit} lnK_{kit}$, which implies that we allow the interaction effect between traffic and the infrastructure capacity variables to be non-linear.

With a dynamic model, we can estimate so-called 'equilibrium cost elasticities' for traffic, where 'equilibrium cost' is used for a situation in which there is no tendency to change maintenance costs, *ceteris paribus* (Odolinski and Wheat (2018)). Hence, the equilibrium cost level is $lnC_{it} = lnC_{it-1} = lnC_{it}^e$. Note that this does not need to be an optimal level of maintenance costs, but it is rather the level chosen by the IM (we still consider that it has the objective of minimizing costs with respect to cost drivers such as traffic). Putting the expression for equilibrium maintenance cost into equation (3), we have

$$lnC_{it}^e = \alpha + \beta_0 lnC_{it}^e + \beta_m lnQ_{mit} + \frac{1}{2}\beta_{mn} lnQ_{mit} lnQ_{nit} + \beta_k lnK_{kit} + \frac{1}{2}\beta_{kp} lnK_{kit} lnK_{pit} + \beta_{km} lnK_{kit} lnQ_{mit} + \sum_{l=1}^{L} \beta_l lnX_{lit} + \frac{1}{2}\sum_{l=1}^{L}\sum_{r=1}^{L} \beta_{lr} lnX_{lit} lnX_{rit} + \sum_{l=1}^{L} \beta_{lm} lnX_{lit} lnQ_{mit} + \sum_{l=1}^{L} \beta_{lk} lnX_{lit} lnK_{kit} + \sum_{d=1}^{D} \vartheta_d Z_{dit} + \mu_i + v_{it}, \tag{5}$$

which can be expressed as

$$lnC_{it}^{e} = \frac{\alpha}{1-\beta_0} + \frac{\beta_1}{1-\beta_0} lnC_{it}^{e} + \frac{\beta_m}{1-\beta_0} lnQ_{mit} + \frac{1}{2}\frac{\beta_{mn}}{1-\beta_0} lnQ_{mit} lnQ_{nit} + \frac{\beta_k}{1-\beta_0} lnK_{kit} +$$

$$\frac{1}{2}\frac{\beta_{kp}}{1-\beta_0} lnK_{kit} lnK_{pit} + \frac{\beta_{km}}{1-\beta_0} lnK_{kit} lnQ_{mit} + \sum_{l=1}^{L} \frac{\beta_l}{1-\beta_0} lnX_{lit} +$$

$$\frac{1}{2}\sum_{l=1}^{L}\sum_{r=1}^{L} \frac{\beta_{lr}}{1-\beta_0} lnX_{lit} lnX_{rit} + \sum_{l=1}^{L} \frac{\beta_{lm}}{1-\beta_0} lnX_{lit} lnQ_{mit} + \sum_{l=1}^{L} \frac{\beta_{lk}}{1-\beta_0} lnX_{lit} lnK_{kit} +$$

$$\sum_{d=1}^{D} \frac{\vartheta_d}{1-\beta_0} Z_{dit} + \frac{\mu_i}{1-\beta_0} + \frac{v_{it}}{1-\beta_0}, \quad (6)$$

The equilibrium cost elasticity for traffic is then

$$\gamma_{it} = \frac{\partial lnC_{it}^{e}}{\partial lnQ_{it}} = \frac{\beta_m}{1-\beta_0} + \frac{\beta_{mn}}{1-\beta_0} lnQ_{it} + \frac{\beta_{km}}{1-\beta_0} lnK_{it}, \quad (7)$$

3.2 Marginal costs

To calculate marginal costs, we use a fitted cost

$$\hat{C}_{it} = \exp(\ln(C_{it}) - \hat{v}_{it} + 0.5\hat{\sigma}^2) \quad (8)$$

which derives from the double-log specification of our model that assumes normally distributed residuals (see Munduch et al. (2002) and Wheat and Smith (2008)). The average cost for gross ton-km is calculated as

$$\widehat{AC}_{it} = \hat{C}_{it}/GTKM_{it} \quad (9)$$

whilst the average cost for train-km is

$$\widehat{AC}_{it} = \hat{C}_{it}/TKM_{it} \tag{10}$$

The marginal cost is calculated by multiplying the average cost by the estimated cost elasticities.

$$MC_{it} = \widehat{AC}_{it} \cdot \hat{\gamma}_{it} \tag{11}$$

A weighted marginal cost is calculated for the entire railway network included in this study:

$$MC_{it}^{W} = MC_{it} \cdot \frac{GTKM_{it}}{(\sum_{it} GTKM_{it})/N} \tag{12}$$

where $GTKM$ is substituted with TKM when calculating the weighted marginal cost per train-km.[5] The weighted marginal cost will generate the same income to the IM as if it would use each observation's marginal cost (eq. 11) for the different track sections.

4. Data

The data has been provided by the Swedish IM and covers a large part of the Swedish railway network during the period 1999 to 2014. Five regional units and a central planning unit within the IM administers the state-owned 14 100 track-km. Information about the infrastructure is available at different levels of detail. Technical aspects of the tracks, such as rail weight, type of sleeper and

[5] Munduch et al. (2002) and Andersson (2008) use a different expression for weighted marginal costs ($MC^{W} = \sum_{it} MC_{it} \cdot \frac{GTKM_{it}}{(\sum_{it} GTKM_{it})}$), which generates the same value as the average value of equation (12). Using equation (12), we can provide average values for different parts of the railway network with respect to capacity utilisation.

quality class are provided for segments of the track that can be shorter than 100 meters, whereas information on costs is available for track sections of the network that comprise 3 to 300 track-km. In total, there are about 250 track sections during the period 1999-2014 (there are changes where sections merge, as well as being divided into new sections). Our dataset does however not include all sections, partly due to missing information, and partly due to the exclusion of marshalling yards, sections closed for traffic, and heritage railways. Moreover, we exclude so called stations sections in our analysis, i.e. sections that have a short route length but many parallel tracks. The reason is that the traffic structure is different compared to most other track sections as these station sections are not only used for overtaking or crossing, but can also be used for shunting, changing locomotives, as well as starting or terminating train services (UIC (2013)). Furthermore, two track sections comprising 29 observations were identified as outliers in the estimations (see next section) and are also excluded from the dataset. In total, we observe on average 162 track sections per year during 1999-2014, comprising on average 11 812 km, which is the majority of the state-owned railway network. Descriptive statistics of our dataset are presented in Table 1.

Information on the technical characteristics of the infrastructure has been collected from the track information system 'BIS' administered by the IM. As mentioned above, this information is available at a more disaggregate level than the cost data, which means that we use weighted averages of variables such as rail weight and quality class in the model estimations made at the track section level. Shares of section track length have been used as weights. Traffic data has been collected from the IM and comprise information on train-km and the gross tonnage of the trains reported by the train operators. We use density measures that are calculated as either gross ton-km/route-km or train-km/route-km; measures that can be described as the average number of gross tons or trains that have run on the entire route length of the section.

Table 1 – Descriptive statistics, track sections, 1999-2014 (2590 observations)

	Median	Mean	St. dev.	Min	Max
Maintenance cost, million SEK in 2014 prices	8.28	11.61	12.29	0.01	110.75
Traffic and line capacity variables					
Train-km, thousand	473	748	847	0	4 778
Ton-km, thousand	169 106	387 882	534 556	1	4 176 261
Train_density (Train-km/Route_length), thousand	10	15	16	0	98
Ton_density (Ton-km/Route_ length), thousand	4 104	6 878	7 321	0	36 356
Dev.50-50TrafficMix_trains (Deviation from 50-50 mix between passenger traffic and freight traffic (trains))	0.35	0.32	0.16	0.00	0.50
Dev.50-50TrafficMix_tons (Deviation from 50-50 mix between passenger traffic and freight traffic (tons))	0.33	0.31	0.16	0.00	0.50
Track_length/Route_ length (Average number of tracks)	1.005	1.236	0.407	1.000	2.587
Pass_Sid (Number of passing sidings)	5.00	6.67	5.83	1.00	40.00
Pass_Sid_Per_Route_l (Passing sidings/Route_length)	0.11	0.14	0.12	0.01	1.11
Infrastructure characteristics and weather					
Route_length, km	47.74	59.72	43.43	0.97	258.10
Track_length, km	57.62	70.91	51.81	1.46	279.35
Switch_length, km	1.17	1.50	1.29	0.06	9.07
Rail_weight, average kg of one meter rail	49.97	51.05	4.99	39.86	60.00
Conc_Sleep_share (Share of track_length with concrete sleepers)	0.83	0.61	0.40	0.00	1.00
Wood_Sleep_share (Share of track_length with wooden sleepers)	0.17	0.39	0.40	0.00	1.00
Slab_Sleep_share (Share of track_ length with slab track)	0.00	0.00	0.00	0.00	0.00
Max_axle_load, tons	22.50	23.10	1.75	16.00	30.00
Qual_average (Average quality class number, 1-6)	3.02	3.00	1.23	1.00	6.00
Snow (mm precipitation when temperature <0° Celcius)	98	112	64	2	344
Organisational variables					
Comp_tend (Dummy when tendered in competition)	0.00	0.48	0.50	0.00	1.00
Mix_tend (Dummy when mix tendered and not tendered in comp.)	0.00	0.06	0.24	0.00	1.00
Region West (Dummy for sections in region West)	0.00	0.18	0.39	0.00	1.00
Region North (Dummy for sections in region North)	0.00	0.13	0.33	0.00	1.00
Region Central (Dummy for sections in region Central)	0.00	0.19	0.40	0.00	1.00
Region South (Dummy for sections in region South)	0.00	0.26	0.44	0.00	1.00
Region East (Dummy for sections in region East)	0.00	0.23	0.42	0.00	1.00

The maintenance cost data include costs for all activities conducted to maintain the rail infrastructure, including snow removal, inspections and minor replacements. Specifically, it includes maintenance of all the infrastructure assets, i.e. tracks (sub- and superstructure), electrification, signalling, and telecommunications. Major replacements are defined as renewals and are not included in this analysis as it requires a different model approach with a different data generating process; see for example Andersson et al. (2012), Andersson et al. (2016) and Odolinski and Wheat (2018) who use corner solution models, survival analysis and vector autoregressive models, respectively.

Starting in 2002, maintenance was gradually exposed to competitive tendering. Odolinski and Smith (2016) found that this reduced costs by about 11 per cent. To control for the impact tendering had on maintenance costs, we include dummy variables indicating when a track section belongs to an area tendered in competition.

Sweden is a large country with climate differences, especially between the northern and southern parts. This can have an impact on the maintenance production, especially since snow removal is included in this study. We have therefore collected weather data from the Swedish Meteorological and Hydrological Institute (SMHI), comprising information on daily mean temperatures and mm of precipitation. We define a variable for snow as mm of precipitation when the daily mean temperature is below 0 degrees Celsius.

5. Results

The dynamic models are estimated with the generalized method of moments (GMM), where we use the System GMM, an approach proposed by Arellano and Bover (1995) and Blundell and Bond (1998). The variables in our models have been divided by their sample median prior to taking a logarithmic transformation. In that way the first order coefficients can be interpreted as elasticities at the sample median. However, the dummy variables and the variables for sleeper type have not been log-transformed. The percentage change in costs from a change in these variables is therefore calculated as $\frac{\Delta C}{C} = 100 \cdot [\exp(\hat{\beta}_k \Delta X_k) - 1]$, where $\hat{\beta}_k$ is the estimated coefficient for variable X_k.

Two models are estimated: in Model 1 we use gross ton density as the traffic variable, whereas train density is the traffic variable in Model 2. In the initial estimations (with 2619 observations), we found that two sections had rather extreme cost elasticities with respect to traffic in Model 1, and these also had a significant impact on the corresponding elasticities for other track sections; dropping these outliers (29 obs.) implied that the number of observations with negative cost elasticities were reduced from 217 to 91. In Model 2, we have 9 observations with negative cost elasticities for traffic, indicating that this model is more well-behaved.

The estimation results are presented in section 5.1 below. All estimations are carried out using Stata 12 (StataCorp, 2011).

5.1 Estimation results

The estimation results are presented in Table 2. First, we can note that the coefficient for lagged maintenance costs is positive and statistically significant in both models, which is in line with the results in previous studies on long panel data sets (see Wheat (2015), Odolinski and Nilsson (2017), and Odolinski and Wheat (2018)).[6] Hence, an increase in a cost driver in year $t-1$ will have an impact on maintenance costs in year t; the IM is not able to adjust its maintenance cost level within the current year after a sudden change in a cost driver. Furthermore, we note that the first order coefficients for route length, switch length, rail weight, snow, and sleeper type (concrete sleepers, with wooden sleepers as baseline), have the expected signs. However, the estimates for snow and concrete sleepers are not statistically significant.

[6] Andersson (2008) found a negative impact using a much shorter panel (years 1999 to 2002).

Table 2 – Econometric results, Models 1 and 2

	Model 1 - Gross tons		*Model 2 - Trains*	
	Coef.	Corr. std. err.	Coef.	Corr. std. err.
Constant	12.2103***	0.9189	12.4795***	0.9001
Maint_Cost_t-1	0.2257***	0.0577	0.2073***	0.0565
Route_l	0.5173***	0.0517	0.5187***	0.0508
Switch_l	0.2117***	0.0349	0.2113***	0.0351
Rail_w	-0.5189*	0.2926	-0.3260	0.2636
Qual_ave	0.0252	0.0423	0.0378	0.0435
Max_axle_load	-0.2261	0.2652	0.0003	0.2890
Conc_sleep_share	-0.0939	0.0659	-0.0710	0.0655
Slab_sleep_share	151.2066	115.3001	148.2963	122.6740
No_of_tracks	0.7873**	0.3318	0.7694**	0.3226
Pass_Sidings_Per_Route_l	0.0369	0.0372	0.0181	0.0351
Dev_50-50_Traffic_Mix	-0.0172	0.0165	0.0003	0.0094
Ton_den	0.1932***	0.0292	-	-
Ton_den^2	0.0184	0.0132	-	-
Ton_denNo_of_tracks	-0.5932**	0.2319	-	-
Ton_den(No_Of_tracks^2)	1.9166***	0.6142	-	-
(Ton_den^2)No_of_tracks	-0.1271***	0.0537	-	-
Train_den	-	-	0.2399***	0.0340
Train_den^2	-	-	0.0308**	0.0127
Train_denNo_of_tracks	-	-	-0.7278**	0.3166
Train_den(No_of_tracks^2)	-	-	2.2340**	0.9687
(Train_den^2)No_of_tracks	-	-	-0.1095	0.0723
Route_l^2	0.1198***	0.0309	0.1250***	0.0339
Route_lSwitch_l	-0.1192***	0.0274	-0.1060***	0.0299
Route_lMax_axle_load	-0.2063	0.2225	-0.0461	0.2435
No_of_tracks^2	-1.7176*	1.0269	-1.7349*	0.9731
Switch_l^2	0.1389***	0.0279	0.1366***	0.0318
Switch_lMax_axle_load	-0.0239	0.1566	-0.1867	0.1776
Max_axle_load^2	6.2435**	2.4258	7.3157**	2.8406
Snow	0.0354	0.0273	0.0395	0.0256
Mix_tend	-0.0141	0.0390	-0.0231	0.0390
Comp_tend	-0.0841**	0.0368	-0.1040***	0.0366
Year dummies 2000-2014	Yes[a]		Yes[a]	
Regional dummies	Yes[b]		Yes[b]	

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

[a] Jointly significant (Model 1: $F(14, 187)=12.41$, $Prob>F=0.000$; Model 2: $F(14, 187)=12.01$, $Prob>F=0.000$

[b] Jointly significant (Model 1: $F(4, 187)=4.82$, $Prob>F=0.001$; Model 2: $F(4, 187)=8.19$, $Prob>F=0.000$

Test of Cobb-Douglas constraint: Model 1: $F(11, 187)=7.88$, $Prob>F=0.000$; Model 2: $F(11, 187)=6.54$, $Prob>F=0.000$

No. of instruments: Model 1 and Model 2 = 59

The quality classification of the railway line (linked to line speed) can be an important factor for maintenance costs (higher speeds may increase wear and tear and is also linked to stricter requirements on track geometry etc.). However, its coefficient (Qual_ave) in the estimations is small and not statistically significant. Here we can note that the correlation coefficients between this variable and the number of tracks, train density and tonnage density are -0.56, -0.41 and -0.40, respectively. Dropping the quality classification variable does not change the estimations results significantly.

Turning to the first order coefficients for the line capacity variables, we can see that the coefficient for the average number of tracks (No_of_tracks) has a positive sign in both models. That is, increasing the number of tracks on a line increases maintenance costs at the sample median, *ceteris paribus,* which is expected as more tracks imply more to maintain. The coefficient for the number of passing sidings per route-km is positive in both models, yet the estimates are rather small and not statistically significant. Moreover, the interaction terms between passing sidings per route-km and traffic were not statistically significant and dropped from the model. The parameter estimate for the level of traffic mix is -0.0172 (p-value 0.299) in Model 1. The negative sign in Model 1 indicates that maintenance costs decrease when the traffic is more homogeneous. One explanation is that a more homogeneous traffic with respect to speeds reduces the capacity utilisation, which then has an impact on the maintenance costs. However, note that the estimate is not statistically significant, and that the coefficient for the corresponding variable is positive and not statistically significant in Model 2.

The first order coefficients for traffic are in line with estimates in the literature on rail infrastructure costs (see Link et al. (2008) and Wheat et al. (2009)). Specifically, the parameter estimate for gross tons is 0.19 and statistically significant at the 1 per cent level, while the estimate for trains is 0.24, also statistically significant at the 1 per cent level. The coefficients show that we have considerable economies of density, where a 10 per cent increase in gross ton density (train density) implies a 1.9 per cent (2.4 per cent) increase in maintenance costs. Importantly, this implies that track sections with a higher traffic density have lower average costs, i.e. cost per ton- or train-km.

To evaluate how the cost elasticities with respect to traffic vary with capacity utilisation, we turn to the coefficients for the interaction terms between the traffic and the infrastructure capacity variables. The parameter estimate for the interaction between gross ton density and number of tracks (Ton_denNo_of_tracks) is -0.5932 and statistically significant at the 5 per cent level. The corresponding estimate in Model 2 – in which train density is the traffic variable – is -0.7278 (statistically significant at the 5 per cent level). The interpretation of the coefficients is that the cost elasticity with respect to traffic is decreasing with the degree of infrastructure capacity, as measured by the average number of tracks, which is in line with the hypothesis in this paper. Note that we also have an interaction between the squared variable for the number of tracks and the traffic variable (Ton_den(No_of_tracks^2)) and Train_den(No_of_tracks^2) in Model 1 and 2, respectively), which is positive in both models – thus, the negative impact this capacity measure has on the cost elasticity for traffic diminishes, and eventually turns slightly positive. We also have an interaction between squared traffic and the number of tracks ((Ton_den^2)No_of_tracks and (Train_den^2)No_of_tracks in Model 1 and 2, respectively), which have negative coefficients in both models (-0.1271 and -0.1095 respectively). These estimates imply that the positive second order effect of traffic diminishes (and turns negative) when the number of tracks increases. The impact of these estimates can be seen in Figures 1 and 2 below, where track sections with an average number of tracks in the interval [1.00, 1.03] have cost elasticities that increase with the traffic volume, whereas track sections with more tracks (interval at [1.03, 2.59]) in Models 1 and 2, respectively, have lower cost elasticities with respect to traffic. In these figures we also include elasticities that are evaluated at the sample median with respect to the average number of tracks on the section (i.e. elasticities from models that are estimated without the interaction terms between traffic and number of tracks). In general, cost elasticities are higher when there are fewer tracks available for a certain traffic volume (i.e. when comparing the elasticities at a certain point on the x-axis in Figures 1 and 2) – that is, when capacity utilisation is higher. One exception is the comparison between the highest intervals [1.13, 1.75] and [1.75, 2.59], which indicates that there are differences in maintenance production costs (strategies) not captured by our model estimations.

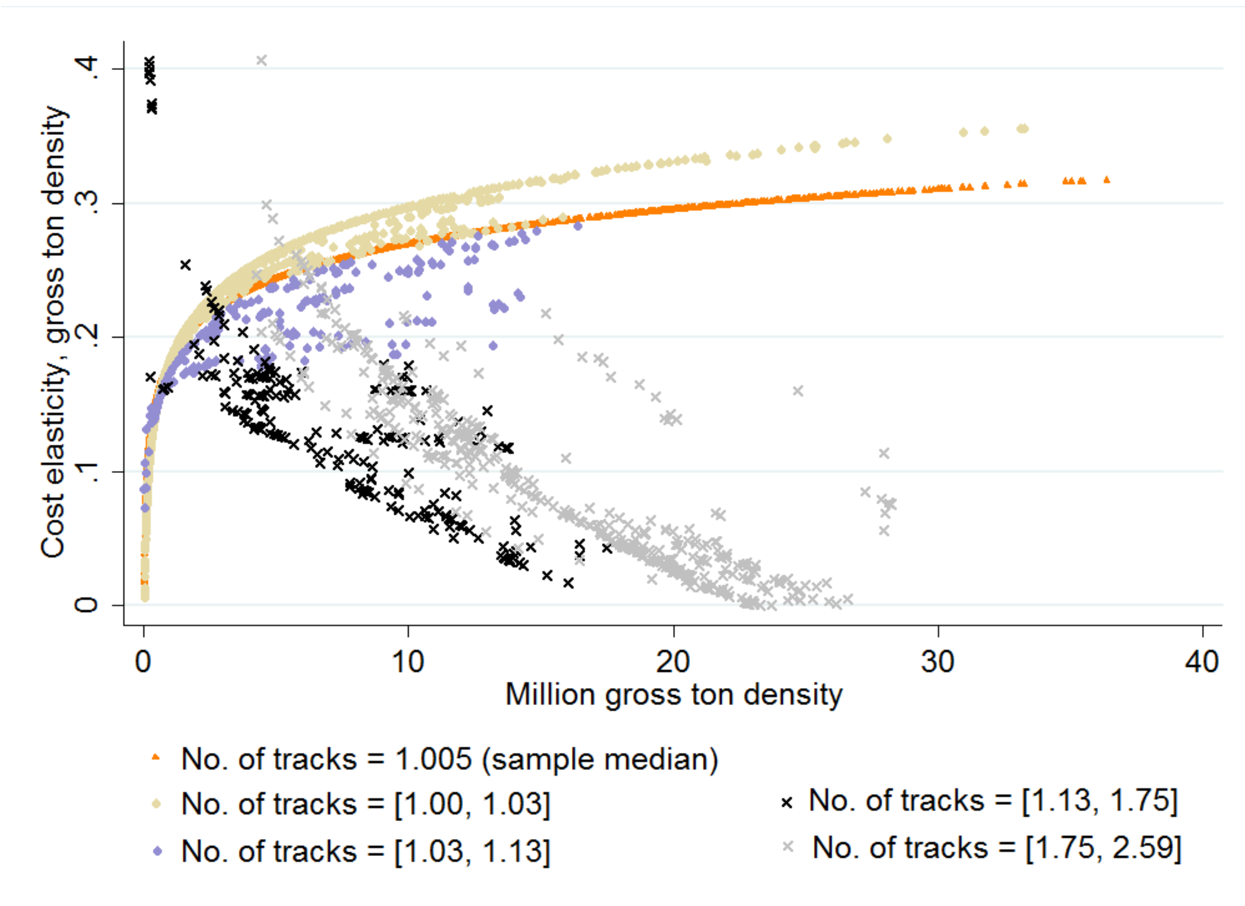

Figure 1 – Cost elasticities with respect to gross ton density (Model 1)[7]

[7] This figure excludes 91 negative cost elasticities with respect to traffic.

As indicated in Figures 1 and 2, excluding the interaction between traffic and the average number of tracks in the estimations implies that the cost elasticities are underestimated for the lowest level of infrastructure capacity (low number of tracks), whereas they are overestimated when the average number of tracks is in the interval [1.03, 2.59]. Interestingly, the cost curves for track sections with an average number of tracks above 1.13 are decreasing with traffic volume. This suggests that these sections have a relatively low capacity utilisation, making a traffic increase less costly compared to the other track sections.

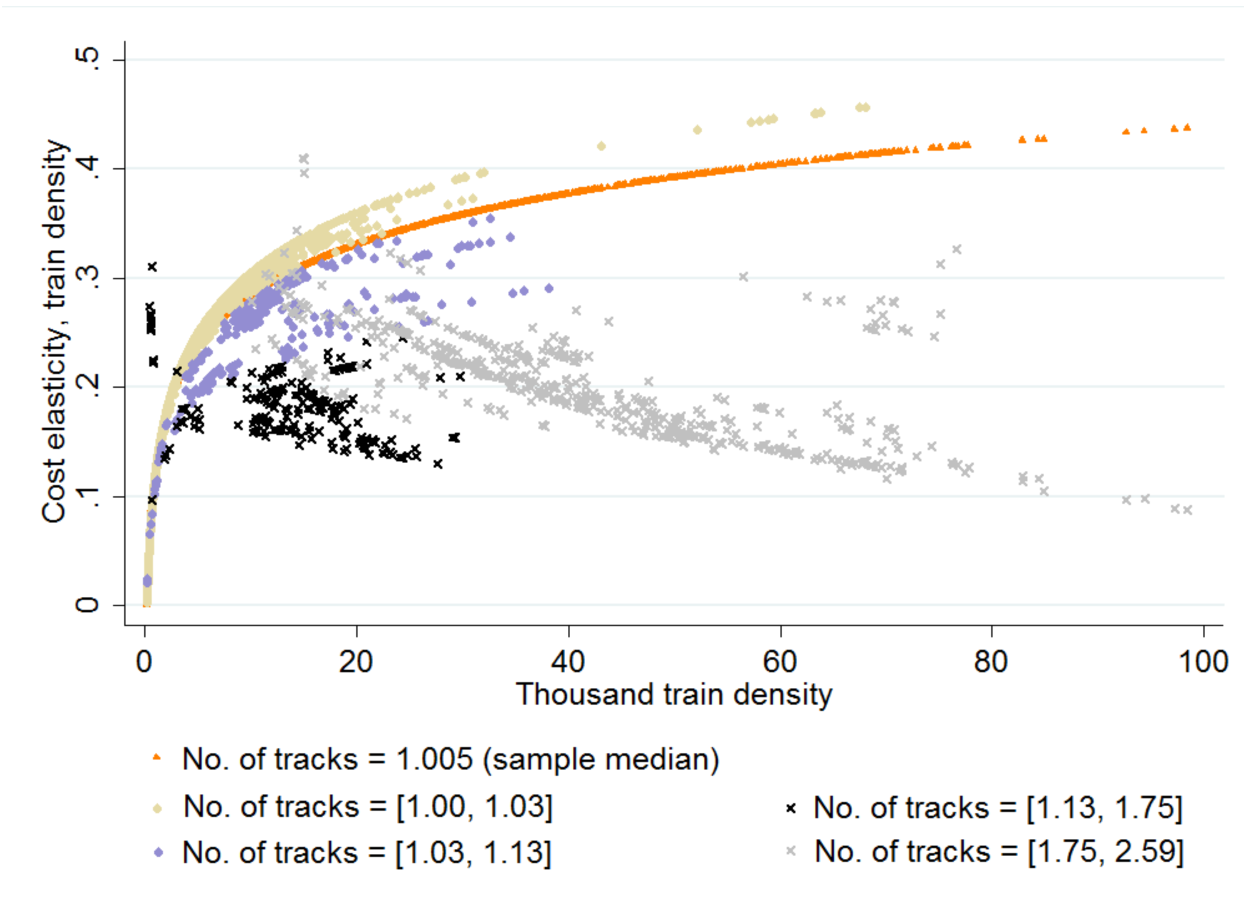

Figure 2 – Cost elasticities with respect to train density (Model 2)[8]

[8] This figure excludes 9 negative cost elasticities with respect to traffic.

5.2 Marginal costs

We calculate the marginal costs by multiplying the estimated equilibrium cost elasticities with the average costs, as described in section 3.2. To evaluate the impact the interaction between traffic and available infrastructure capacity (i.e. capacity utilisation) has on the marginal costs, we also calculate marginal costs using equilibrium cost elasticities that are evaluated at the sample median of infrastructure capacity. That is, the interaction terms between traffic and the number of tracks has been excluded from the estimations.

Table 3 – Average costs (AC) and weighted marginal costs (WMC), SEK

	Variable	Mean	Std. Err.
Model 1	AC	0.3437	0.0902
(Gross ton-km)	AC (excl. traffic and capacity interactions)	0.3332	0.0848
	WMC	0.0050	0.0001
	WMC (excl. traffic and capacity interactions)	0.0070	0.0001
Model 2	AC	122.0158	34.6933
(Train-km)	AC (excl. traffic and capacity interactions)	117.2605	32.4144
	WMC	3.5316	0.0670
	WMC (excl. traffic and capacity interactions)	4.3565	0.0854

The average costs and the weighted marginal costs are presented in Table 3. The weighted marginal cost per gross ton-km is SEK 0.0050, while the weighted marginal cost per train-km is SEK 3.5316. These costs are higher when we exclude the interaction terms between traffic and number of tracks in the estimations.

To evaluate the impact capacity utilisation has on marginal costs, we plot these costs against traffic volume and differentiate with respect to the average number of tracks on a section. See Figures 3 and 4 below, where the observations in the figures correspond to a weighted marginal cost for each track section (i) in each year (t).

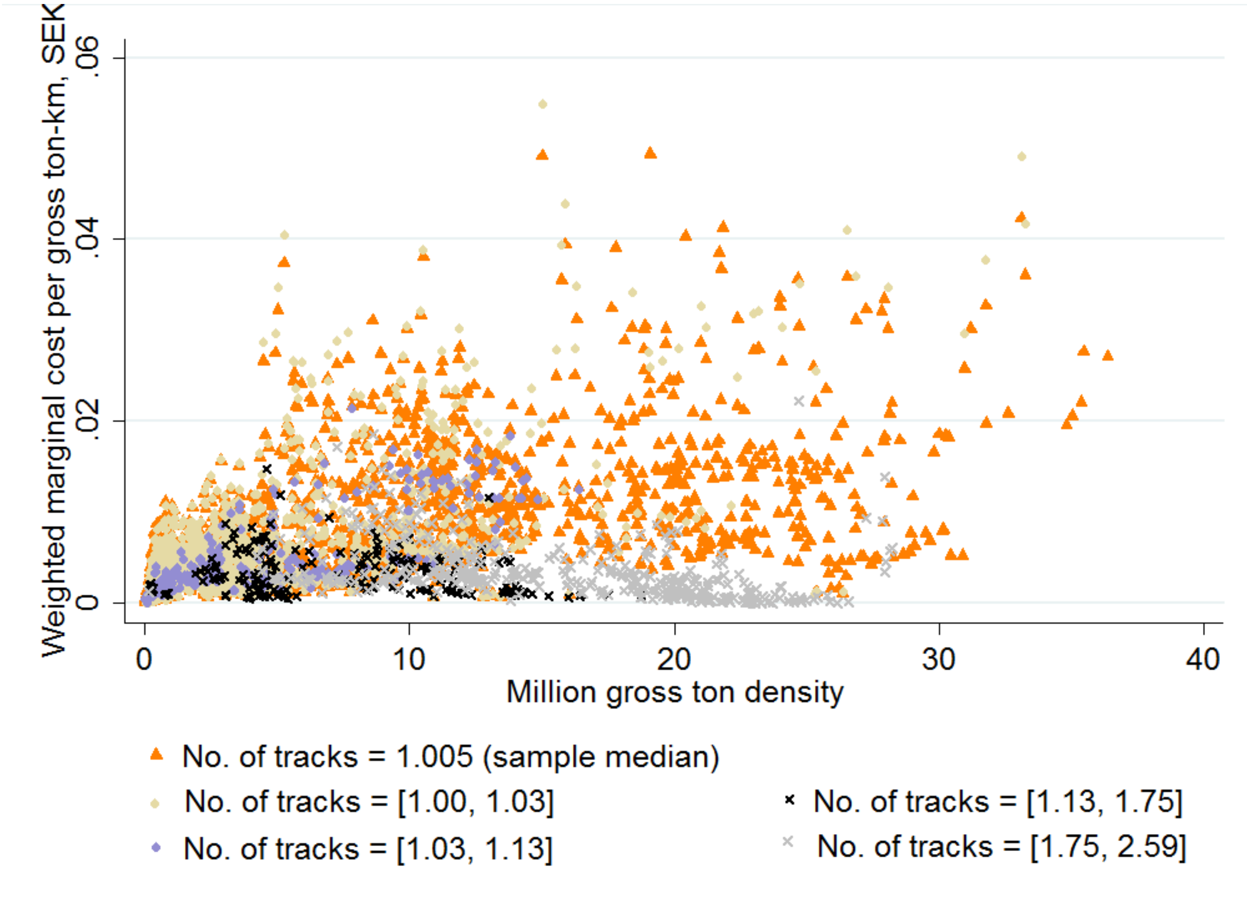

Figure 3 – Weighted marginal cost per gross ton-km, SEK (Model 1)

Figure 3 shows that the weighted marginal cost per gross ton-km increases with traffic volume and that these costs are generally higher for track sections with a lower average number of tracks (that is, comparing the marginal costs at certain point on the x-axis). Figure 4 shows the same relationship between capacity utilisation and weighted marginal costs per train-km.

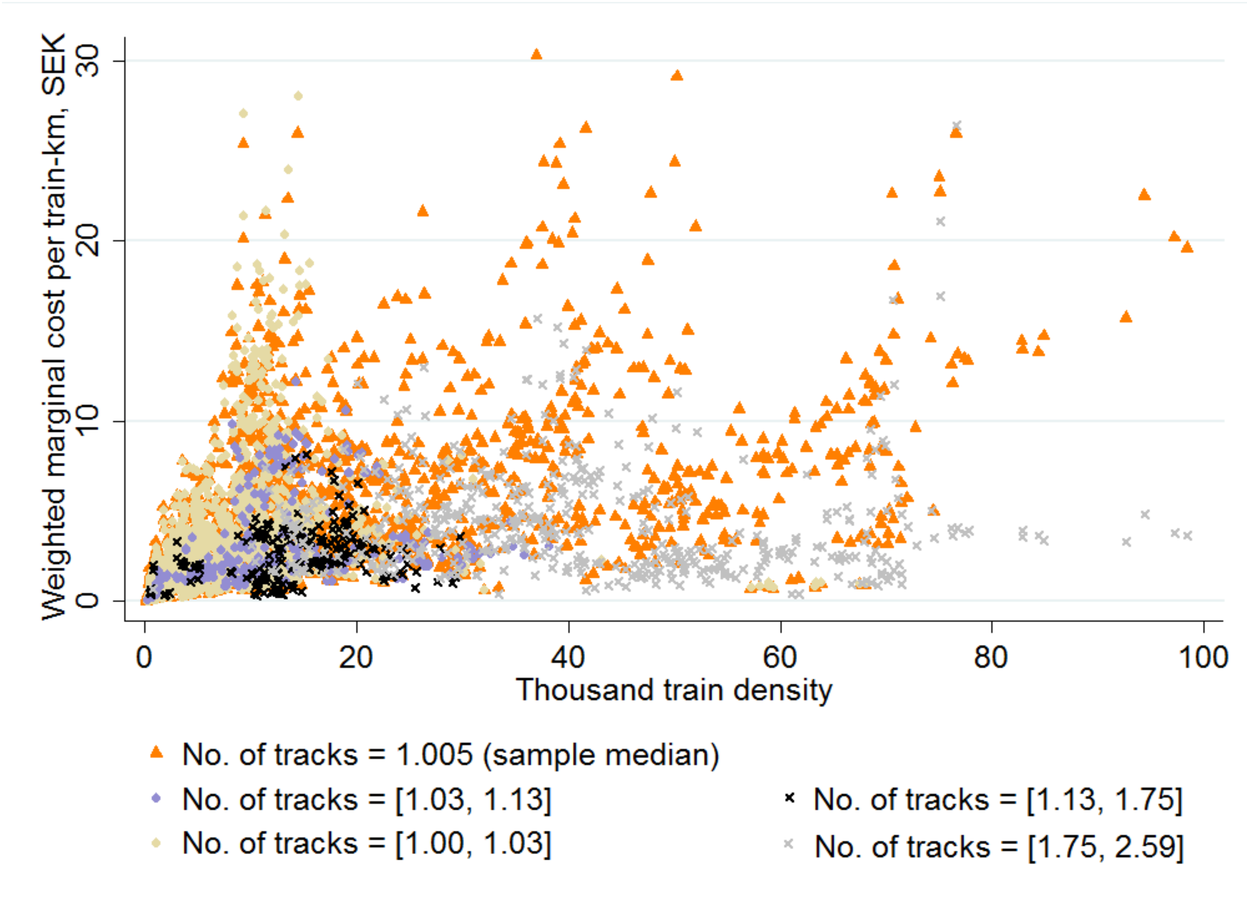

Figure 4 – Weighted marginal cost per train-km, SEK (Model 2)

The differences in weighted marginal costs with respect to capacity utilisation are slightly more apparent in Tables 4 and 5, in which we have grouped the observations based on traffic volume and the average number of tracks. In line with the relationships in Figures 1 and 2, the weighted marginal costs are generally increasing with capacity utilisation (going from the top left to the bottom right of the table), except when comparing marginal costs between the highest intervals [1.13, 1.75] and [1.75, 2.59].

Table 4 – Weighted marginal costs per gross ton-km (SEK) and number of observations with respect to capacity utilisation

		Weighted marginal cost				*Number of observations*			
		Million gross ton density				Million gross ton density			
		[0, 2.5)	[2.5, 5)	[5, 7.5)	[7.5, 36]	[0, 2.5)	[2.5, 5)	[5, 7.5)	[7.5, 36]
No. of tracks	[1.75, 2.59)	0.0013	0.0051	0.0045	0.0027	1	6	24	427
	[1.13, 1.75)	0.0021	0.0039	0.0037	0.0031	15	61	17	100
	[1.03, 1.13)	0.0023	0.0049	0.0046	0.0111	98	51	38	60
	[1.00, 1.03)	0.0030	0.0051	0.0088	0.0130	720	375	138	253

Table 5 – Weighted marginal costs per train-km (SEK) and number of observations with respect to capacity utilisation

		Weighted marginal cost			*Number of observations*		
		Thousand train density			Thousand train density		
		[0, 7.5)	[7.5, 15)	[15, 98)	[0, 7.5)	[7.5, 15)	[15, 98)
No. of tracks	[1.75, 2.59)	0.6745	3.5655	4.5800	1	27	430
	[1.13, 1.75)	1.4187	2.3168	3.1225	26	81	86
	[1.03, 1.13)	1.3449	4.3324	3.8856	70	112	65
	[1.00, 1.03)	1.9310	5.1307	4.2598	776	580	130

6. Conclusions

Differences in line capacity utilisation imply different production environments and thus have an effect on maintenance costs. Previous studies on marginal maintenance costs for rail infrastructure usage have, however, focused on the wear and tear caused by traffic. This paper therefore contributes to the literature by estimating the impact line capacity utilisation has on maintenance costs. Specifically, the marginal maintenance cost for traffic is increasing with capacity utilisation, which may be due to more fragmented possession times for maintenance or being restricted to possession times during night (which implies higher labour costs) when capacity utilisation is high during daytime. This increase in marginal costs can also be due to a strategy to carry out more (preventive) maintenance when capacity utilisation increases, as these tracks are generally more sensitive to delays – that is, the risk of large user costs motivates the increased maintenance.

The models estimated in this paper use either gross tons or trains as the traffic measure, where the former captures the impact on wear and tear better than the latter, whereas the number of trains is a better measure for capacity utilisation. Still, both traffic measures result in marginal costs that are increasing with capacity utilisation. Furthermore, the results indicate that a model that does not acknowledge the interaction between traffic and infrastructure capacity (as measured by the number of tracks) leads to biased estimates of marginal costs, considering that such a model omits an important variable that is correlated with traffic.

The results in this paper are significant considering that track access charges can be based on marginal costs. Setting charges based on marginal costs that are differentiated with respect to capacity utilisation may well change the behaviour of the operators, and thus lead to a more efficient use of the infrastructure.

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