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Marginal Railway Infrastructure Costs in a Dynamic Context

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In this paper, dynamic aspects of railway infrastructure operation and maintenance costs in Sweden are explored. Econometric cost functions are estimated to check the robustness of previous marginal cost estimates by introducing lags and leads of both dependent and independent variables. We find support for a forward-looking behaviour within the Swedish National Rail Administration (Banverket) as both infrastructure operation and maintenance costs are reduced prior to a major renewal. There are also indications of both lagged traffic and costs affecting the cost structure.

Keywords: railway; infrastructure operation; maintenance; marginal costs; panel data

1. Introduction

Marginal cost estimation of railway infrastructure wear and tear is an important task in the light of the European railway policy (European Parliament, 2001). The Swedish Rail Administration (Banverket) annually spent 2.7 billion Swedish Kronor (SEK) on maintenance and SEK 1 billion on renewals between 2004 and 2006 (Banverket, 2007).[2] Some of these costs are related to direct wear and tear from traffic, for which rail operators should be charged according to the marginal cost principle. Banverket currently charges train operators SEK 0.0029 per gross tonne kilometre for infrastructure wear and tear. Andersson (2006, 2007a, 2007b) estimates the marginal cost of wear and tear in Sweden using pooled ordinary least squares (POLS), fixed effects (FE) and survival analysis (SA). Although these models all include a variety of traffic and infrastructure variables, they exclude dynamic aspects on the cost structure i.e. they ignore the possibility of the cost level in time t being affected by costs or other aspects in other time periods, $t \pm m$.

The purpose of this paper is to extend the work in Andersson (2006, 2007a) by introducing lags and leads of dependent and independent variables as an explanation for railway infrastructure costs in Sweden. Based on discussions with staff at the Swedish National Rail Administration (Banverket), we have reason to believe that the cost structure have dynamic dimensions, which could affect the previously estimated models. We make use of both static and dynamic panel data

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[2] The exchange rate from Swedish Kronor (SEK) to Euro (EUR) is SEK 9.49/EUR and from Swedish Kronor to US Dollar (USD) is SEK 6.01/USD (June 30, 2007).

models when exploring potential dynamic effects. The outcome of these analyses will provide an indication of how robust previous elasticity and marginal cost estimates are.

The outline of the paper is as follows. Section 2 makes a brief review of previous work in this field followed by a description of our data in section 3. Hypotheses of dynamics are outlined in section 4. The econometric models and associated results are presented in section 5, and we discuss the results and draw conclusions in section 6.

2. Literature review

This paper builds on recent work on the cost structure of vertically separated railway organisations. There has been increasing activity in the field of marginal railway cost estimation in Europe during the last decade (Link and Nilsson, 2005). This has grown out of a sequel of projects funded by the European Commission in line with the European railway policy (European Parliament, 2001). The work so far has been devoted to setting the framework for transport system pricing (Nash and Sansom, 2001), linking cost accounts in member states to match the needs of marginal cost estimation (Nash, 2003), finding best practices in member states (Thomas et al., 2003) and disseminating findings (Nash and Matthews, 2005). Still, there are only a limited number of empirical studies related to marginal railway infrastructure costs using micro-level data (Lindberg, 2006).

The paper that initiated both recent and current research is Johansson and Nilsson (2004).[3] The general approach is to do regression analysis on maintenance costs and control for infrastructure characteristics and traffic volumes. Johansson and Nilsson (2004) estimate cost functions on data from Sweden and Finland covering the years 1994-1996 and 1997-1999 respectively. They apply the method of pooled ordinary least squares (POLS) in their analysis and derive cost elasticities with respect to output and associated marginal costs by pooling annual data for three years and using a reduced form of Translog specification by Christensen et al. (1973). Traffic volumes in terms of gross tonnes and trains are considered as outputs of the track, and costs are assumed to be minimised for a given level of output.[4]

Munduch et al. (2002) use a Cobb-Douglas specification on 220 annual observations from the Austrian Railways between 1998 and 2000. The data consists of track maintenance costs, traffic volumes in gross tonnes, and a rich set of infrastructure variables. Pooled estimates are compared to annual estimates and tests favour the former. They also test for and reject the use of gross tonne kilometres as output, and suggest gross tonnes and track kilometres as separate variables.

Daljord (2003) estimates Cobb-Douglas and Translog functions on Norwegian maintenance cost data from 1999 to 2001, but is heavily restricted in his analysis by data availability. He concludes that there is a need for a dedicated data collection strategy in Norway to come to terms with the evident problems in the data used.

Tervonen and Idström (2004) analyse the cost structure of the Finnish railway network with data from 2000 to 2002, using a Cobb-Douglas function. They differ in their approach by a priori identifying fixed and variable cost groups, and only analysing variable costs. The analysis is based on maintenance costs as well as an aggregate of maintenance and renewal. Their main conclusion is that marginal costs have decreased compared to analyses undertaken on data from 1997 to 1999, but the reduction might come from changes in cost accounts.

[3] The work by Johansson and Nilsson was done in the late 1990's and the working paper that circulated then initiated the following studies, although the journal article was published in 2004.
[4] The reason Johansson and Nilsson put forward in favour of excluding factor prices is the harmonisation of prices through a highly regulated labour market. Track sections are assumed to have a similar price structure when compared to each other.

Andersson (2006) updates the estimates by Johansson and Nilsson (2004) with data from 1999 to 2002 and finds that a separation of maintenance and infrastructure operation costs is warranted as the latter is driven by trains rather than gross tonnes.[5] The new data set also includes renewal costs, and models are estimated for infrastructure operation, maintenance as well as an aggregate of maintenance and renewals using POLS.

Marti and Neuenschwander (2006) estimate a POLS model for maintenance cost data on the Swiss national network during 2003-2005. A rich set of infrastructure variables and traffic is used to explain cost variation.

While the studies above make use of micro-level data (track sections), the study by Wheat and Smith (2008) use data from 53 maintenance delivery units for the Great British Network in 2005/06 and apply OLS. They find somewhat higher elasticities than the other studies, but use track maintenance costs, which is a more narrow cost base.

Considering the variation between the individual studies, the results have been reasonably similar in terms of cost elasticities with respect to output, when controlling for the cost base included (Wheat, 2007). There seems to be evidence for the maintenance cost elasticity with respect to output of gross tonnes to be in the range of 0.2 - 0.3, i.e. a 10 percent change in output gives rise to a 2-3 percent change in maintenance costs. Marginal costs on the other hand vary between countries and are more difficult to compare.

Lately, there has been some alternative econometric approaches to the one suggested by Johansson and Nilsson (2004). Gaudry and Quinet (2003) use a very large data set for French railways in 1999, and explore a variety of unrestricted generalised Box-Cox models to allocate maintenance costs to different traffic classes. They reject the Translog specification as being too restrictive on their data set. Andersson (2007a) estimates infrastructure operation and maintenance cost models using panel data techniques and rejects the POLS approach. He finds significant heterogeneity in the data and estimates marginal maintenance costs twice as high as previous estimates in Andersson (2006) using POLS.

3. Data

A panel (a combination of cross-sectional and time-series data) of track section data with cost, infrastructure and traffic information on the Swedish railway network over 1999-2002 is available. Track sections are lines and stations of different sizes that together form the main network, ranging in length from 2 to 240 kilometres. This data has previously been used in Andersson (2006, 2007a) for cost function estimations. The infrastructure data consists of variables such as track section length, number of switches, curvature, rails and sleeper models. We will though not use this data explicitly as the modelling approach combined with the nature of this data makes it possible for us to handle the infrastructure information without actually including any individual infrastructure variables (see section 4 for modelling details).

In this study, we will make use of additional information on renewal costs in 2003 and 2004, and also maintenance costs in 1995 – 1998 to create indicator variables for future major renewals. Table 1 presents the main cost and traffic variables used in the analyses. The traffic data comprises gross tonne volumes and number of trains per track section observed between 1999 and 2002. Cost data on infrastructure operation, maintenance and renewal is available for roughly 185 track sections per year from 1999 to 2002. Infrastructure operation is dominated by snow removal (80 %). Activities in this cost group have a very short time horizon and are

[5] Infrastructure operation was chosen in Andersson (2006) as the terminology used for short-term maintenance, which is dominated by winter maintenance such as de-icing and snow removal. For consistency we will keep this definition.

undertaken to keep the track open for train movements. Maintenance activities have a somewhat longer time horizon and are in most cases needed at least once biannually in order to prevent the track from premature degradation. Tamping, ballast cleaning and switch overhaul fall into this category. Finally, renewal activities have a longer time horizon and are undertaken every 20-60 years. A renewal is an activity aiming at bringing the track back to its original condition. Rail, sleeper and switch replacements are examples of track renewal activities.

Table 1. Cost and traffic data (1995-2004).

Variable	Mean	Std. Dev.	Min.	Max.	No. obs.
Infrastructure operation costs 1999	1 211 088	1 692 148	171.6	12 882 900	186
Infrastructure operation costs 2000	731 378	1 189 766	1 297.6	8 542 290	186
Infrastructure operation costs 2001	832 074	1 133 303	1 899.7	7 497 993	188
Infrastructure operation costs 2002	922 302	1 309 568	5 433.0	10 782 100	189
Maintenance costs 1995	6 163 042	5 963 953	67 450.6	40 251 920	182
Maintenance costs 1996	5 857 501	5 378 465	255 750.0	36 818 408	182
Maintenance costs 1997	6 035 803	5 410 725	243 855.4	33 547 084	185
Maintenance costs 1998	6 298 780	5 865 820	20 168.1	42 835 968	187
Maintenance costs 1999	6 398 248	6 376 953	73 956.2	52 591 399	186
Maintenance costs 2000	6 135 850	5 593 475	267 001.0	40 142 000	186
Maintenance costs 2001	6 726 822	6 823 102	54 394.6	57 766 782	188
Maintenance costs 2002	8 822 253	10 168 663	164 929.0	80 852 300	189
Renewal costs 1999	2 876 978	11 013 842	0	130 472 463	186
Renewal costs 2000	4 171 920	15 670 933	0	136 522 000	186
Renewal costs 2001	4 475 164	12 913 218	0	93 955 721	188
Renewal costs 2002	3 801 761	9 638 315	0	96 695 305	189
Renewal costs 2003	3 923 292	11 571 754	0	130 115 896	190
Renewal costs 2004	4 653 710	17 632 176	0	215 508 192	190
Total gross tonnes 1999	7 112 086	9 349 813	6 427	88 459 900	186
Total gross tonnes 2000	7 494 826	9 391 651	27 611	77 900 657	186
Total gross tonnes 2001	7 570 121	9 522 643	29 169	83 727 375	188
Total gross tonnes 2002	7 603 059	9 700 020	21 077	83 659 211	189
Total number of trains 1999	14 396	18 605	15	155 142	186
Total number of trains 2000	14 953	19 143	50	152 933	186
Total number of trains 2001	16 141	20 834	41	167 602	188
Total number of trains 2002	16 484	22 105	29	185 681	189

Source: *Banverket*. Costs are in SEK and 2002 prices.

4. Hypotheses of dynamics

In this section we will present a variety of aspects on dynamics in rail infrastructure costs, which affects the modelling approach. If we look at the data at hand, we have the infrastructure characteristics, costs and traffic. Starting with the infrastructure, the development of a railway network is a slow process over time. Andersson (2007a) estimated infrastructure characteristics as a fixed effect for 1999-2002, i.e. time invariant for the period. This decision was based on empirical evidence of negligible within-track section variation for the observed infrastructure variables. Hence, we assume a static infrastructure. Given the fact that we have a panel data set, estimating track section specific constants (fixed effects) will cover the infrastructure's effect on the cost structure and we do not need to explicitly model all infrastructure variables of interest. Traffic, on the other hand, is expected to vary over time, although the main flows are fairly stable, and needs to be included in our models.

There is an interrelationship between infrastructure operation, maintenance and renewal costs. These categories are basically short-term, medium-term and long-term actions to preserve the railway track, and the money allocated to one category affects the money needed for the other two. This interrelationship is particularly strong between maintenance and renewals, where lack of maintenance will increase deterioration rates and force premature track renewals.

In this paper, we will explore three dynamic aspects that might affect the observed cost structure and therefore marginal cost estimates. A variety of model specifications are used in order to test these hypotheses. Models with lags and leads of both dependent and independent variables are explored; hence different models are used for different questions posed.

The first hypothesis is that infrastructure operation and maintenance costs in time t depend not only on covariates in time t, but also on whether a major renewal is planned in the near future, $t+1$ or $t+2$. This forward-looking behaviour could be part of a cost-minimising strategy, which includes reducing maintenance costs as the time of a track renewal is approached. There is no outright Banverket policy that states how much maintenance can be reduced and it might eventually lead to increased track degradation and derailment risks. Common knowledge though within track managers' circles is that this strategy is safe to run for a few years. Thus, the hypothesis is that future renewal costs will *lead* current infrastructure operation and maintenance costs. Track managers are aware of forthcoming renewals as they are a part of a three-year rolling planning process. This gives them time to decide on maintenance levels in advance. There is no standard way of defining the level of renewals required to actually affect maintenance costs, but discussions with track managers give the following approach. Dummy variables for major renewals, $D_{it,m}^{R}$, are generated based on a comparison of a three-year moving average of annual maintenance costs in t - 2 (C_{it-2}^{M}), t - 3 (C_{it-3}^{M}) and t - 4 (C_{it-4}^{M}), and annual renewals in $t+1$ ($m=1$), C_{it+1}^{R}, and $t+2$ ($m=2$), C_{it+2}^{R}, for each observation. If renewal costs are at least two times higher than the moving average of maintenance costs, this is identified as a major renewal (1).

$$D_{it,m}^{R}=\begin{cases} 1\text{ if } C_{it+m}^{R}>2\cdot\left(\sum_{t=-2}^{-4}C_{it}^{M}\ /3\right) & m=1,2 \\ 0\text{ if } C_{it+m}^{R}\leq 2\cdot\left(\sum_{t=-2}^{-4}C_{it}^{M}\ /3\right) & m=1,2 \end{cases} \qquad (1)$$

By using a three-year moving average of lagged maintenance costs (t - 2 – t - 4), we avoid endogeneity problems, which would appear if we include maintenance costs in t or t - 1 in the creation of the dummy variable. An alternative to using maintenance costs as a reference is to use an average of renewal costs over a longer time period. This approach is more uncertain due to the short time frame in our data and the strong volatility in renewals.

A negative relationship between maintenance costs in t and major renewals in $t+1$ and $t+2$ is expected, but there are uncertainties a priori about what effect this forward-looking behaviour will have on infrastructure operation costs, if any. Apart from winter maintenance, infrastructure operation involves short-term maintenance, which one can suspect either to increase or decrease as a reaction to reduced maintenance (if we find evidence of this). A carefully planned reduction in maintenance will open up for a parallel reduction in infrastructure operation costs, but if the maintenance reduction is taken too far we might also observe increased infrastructure operation costs as a backlash.

This analysis poses no specific problems related to the econometric model specification. The dummy variables for renewals are exogenous variables and this model can be estimated using a fixed effects estimator as in Andersson (2007a).

$$y_{it} = \mathbf{x}'_{it}\boldsymbol{\beta} + \mathbf{z}'_i\boldsymbol{\alpha} + \varepsilon_{it}, \qquad i = 1, 2, ..., N \qquad t = 1, 2, ..., T \tag{2}$$

y is our dependent variable, $\mathbf{x}$ is a vector of explanatory variables, $\mathbf{z}$ is a vector that captures observed or unobserved heterogeneity and ε is the error term. If $\mathbf{z}_i$ in (2) contains an unobserved effect that is correlated with $\mathbf{x}_{it}$, we can use an individual specific constant, α_i, as in expression (3) to get unbiased and consistent estimates of all model parameters. See Wooldridge (2002) or Greene (2003) for an exhaustive presentation of fixed effects estimation.

$$y_{it} = \alpha_i + \mathbf{x}'_{it}\boldsymbol{\beta} + \varepsilon_{it}, \qquad i = 1, 2, ..., N \qquad t = 1, 2, ..., T \tag{3}$$

An alternative to fixed effects estimation is random effects estimation. The choice between these two estimators depends on assumptions about the correlation between the unobserved effect and included covariates. A common way of dealing with this choice is to use a test suggested by Hausman (1978). This test is applied in previous work (Andersson, 2007a) in favour of the fixed effects approach and we build on that result in this work.

The second hypothesis is that maintenance costs in t might be affected by traffic not only in t, but also in t - 1. Hence, we assume that there is some reaction time for actions in response to observed traffic levels. The short time panel available is a restriction and the analysis is therefore limited to a one-year lag structure. A variety of specifications for maintenance costs will be investigated. This hypothesis will also be analysed using the fixed effect model in (3), but is not applied to infrastructure operation costs, as it is hard to justify such a dynamic relationship for short-term and winter maintenance.

The third hypothesis is linked to the nature of maintenance itself. Some maintenance activities are not needed on an annual basis, which means that there will be fluctuations in maintenance costs between years, even if traffic volumes are constant. Also, if too little is spent on maintenance one year it will come out as a need to spend more the coming year. This cyclic behaviour will continue in order to keep the railway track in a steady-state condition over time. If this hypothesis holds, costs in year t will depend on costs in year $t-1$, and exploring a lag structure of the dependent variable is warranted. For this type of cyclic fluctuations, we expect a negative coefficient for the lagged variable, and for the process to be stationary the estimated coefficient has to be between -1 and 0 (Vandaele, 1983). The size of the coefficient signals the importance of historical maintenance. The further away from 0, the more important is the history. A positive estimate indicates a trend in costs over time, while a negative estimate shows that the cost is oscillating around some mean value over time. Once again, this hypothesis is not applied to infrastructure operation costs.

The third hypothesis introduces special problems with autocorrelation between the error term and the lagged dependent variable through the group specific effect, but Arellano and Bond (1991) suggested a generalised method of moments (GMM) estimator for this type of problem, which involves taking first differences of the model to sweep away heterogeneity in the data.
Consider a model where a dynamic relationship in y is captured through a lagged dependent variable as a regressor (4),

$$y_{it} = \delta y_{it-1} + \mathbf{x}'_{it}\boldsymbol{\beta} + \varepsilon_{it}, \qquad i = 1, 2, ..., N \qquad t = 1, 2, ..., T \tag{4}$$

where δ and $\boldsymbol{\beta}$ are parameters to be estimated, $\mathbf{x}_{it}$ is a vector of explanatory variables for observation i in time t, is a vector . Assume that the error term ε_{it} follows a one-way error component model $\varepsilon_{it} = \mu_i + \nu_{it}$ where μ_i is IID (0, σ_μ^2) and ν_{it} is IID (0, σ_ν^2) independent of each other and among themselves.

This model will include two effects that persist over time, autocorrelation from using a lagged dependent variable and heterogeneity from the individual effect μ_i. Autocorrelation comes from y_{it} being a function of μ_i and subsequently y_{it-1} also being a function of μ_i. Therefore, the regressor y_{it-1} in (4) is correlated with the error term ε_{it}. This will make an OLS regression biased and inconsistent. Furthermore, Baltagi (2005) shows that both standard FE and RE estimation of expression (4) will be biased, but a solution proposed to these problems is first-differencing, which will sweep away the individual effect and using lagged instruments[6] to handle the autocorrelation.

Arellano and Bond's (1991) dynamic panel data estimator does exactly the above, but also use the orthogonality between lagged values of y_{it} and ν_{it} to create additional instruments. A simple autoregressive version of (4) with the same error structure, but without regressors, is given in (5).

$$y_{it} = \delta y_{it-1} + \varepsilon_{it}, \qquad i = 1, 2, ..., N \qquad t = 1, 2, ..., T \tag{5}$$

To consistently estimate δ, take first differences of (5) to eliminate the individual effect μ_i, which will make the second term on the right-hand side in (6) equal to zero.

$$(y_{it} - y_{it-1}) = \delta(y_{it-1} - y_{it-2}) + \overbrace{(\mu_i - \mu_i)}^{0} + (\nu_{it} - \nu_{it-1}) \tag{6}$$

In order to find valid instruments to the lagged differenced regressor (that are uncorrelated with the differenced error term), $T \geq 3$ is needed. $T = 3$ gives the following model (7),

$$(y_{i3} - y_{i2}) = \delta(y_{i2} - y_{i1}) + (\nu_{i3} - \nu_{i2}). \tag{7}$$

y_{i1} is highly correlated with $(y_{i2} - y_{i1})$ and a valid instrument, but at the same time uncorrelated with $(\nu_{i3} - \nu_{i2})$. If T is extended, the list of instruments is extended. With $T = 4$, both y_{i1} and y_{i2} are valid instruments to the regressor $(y_{i3} - y_{i2})$ and one can go on like this by adding more instruments as T increases.

If we add other regressors ($\mathbf{x}_{it}$) to the Arellano and Bond model that are correlated with the individual effect, then these can also be used as instruments if they are *strictly exogenous*, $E(\mathbf{x}_{it}\ \varepsilon_{is}) = 0 \ \forall\ t, s = 1, 2, \ldots, T$. This approach can also be adjusted if some or all instruments are considered *predetermined* $E(\mathbf{x}_{it}\ \varepsilon_{is}) \neq 0$ for $t < s$ and zero otherwise (see chapter 8 in Baltagi, 2005 for further details).

5. Model specifications and estimation results

The hypotheses presented in section 4 are incorporated into econometric models that can be estimated using static and dynamic panel data techniques. Models and results for maintenance are presented in section 5.1, and for infrastructure operation in section 5.2. All model estimations are done using *Stata 9.2* (StataCorp, 2005) and costs are expressed in 2002 real prices.

[6] An instrument is a variable that does not belong to the regression itself, but is correlated with y_{it-1}, and uncorrelated with ε_{it}.

5.1 Maintenance costs

In this sub-section, models for maintenance costs are explored. Firstly, the effect on maintenance costs from future renewals is analysed. Secondly, we introduce lagged traffic variables and thirdly, add a lagged dependent variable to the model.

5.1.1 Maintenance costs and future renewals - Model I

In this sub-section, a model for maintenance costs in the presence of planned future renewals is explored to check for forward-looking behaviour through reduced maintenance costs. A logarithmic model for maintenance costs (C^M) is specified in expression (8), using total gross tonnes (*TGT*) as output variable. In section 4, we discussed the static nature of the infrastructure. This holds for one exception, the age of the track. This variable will change not only from time passing by, but also from major track renewals. For this reason, *rail age* is added to the model as a proxy for track age as we a priori anticipate age to have a negative impact on maintenance costs, other things equal. We have initially specified a model with a third-degree polynomial for traffic, as in Andersson (2007a), rail age and dummy variables for future renewals. The dummy for year t + 2 is though insignificant and based on Akaike's (AIC) and Bayes' (BIC) Information Criteria, the model is rejected in favour of the specification in (8). Estimates are given in Table 2.

$$\ln C_{it}^{M} = \alpha_i + \beta_1 \ln TGT_{it} + \beta_2 (\ln TGT_{it})^2 + \beta_3 (\ln TGT_{it})^3 + \beta_4 \ln RailAge_{it} + \phi_1 D_{it,1}^{R} + \varepsilon_{it} \tag{8}$$

Table 2. Results from a FE model for infrastructure maintenance costs and a renewal dummy - *Model I*

Variable	Coefficient	(Robust S.E.)
ln *TGT*	7.499868†	(3.619658)
(ln *TGT*)^2	-0.575396†	(0.277199)
(ln *TGT*)^3	0.014685†	(0.006942)
ln *Rail age*	0.125651*	(0.064497)
Renewal$_{t+1}$	-0.159739‡	(0.051687)
	Observations = 749	Groups = 190
	F (5, 554) = 4.65	prob. > F = 0.0004
Correlation between unobserved effect and included covariates = 0.16		
σ_α = 0.919 σ_ε = 0.349 ρ = 0.874		

Legend: ‡ Significant at 1% level; † Significant at 5% level; * Significant at 10% level

The estimated coefficients for gross tonnes have expected signs and are significant at the 5 percent level. The coefficient for rail age is significant at the 10 percent level, and implies that a 10 percent increase in age gives a 1.2 percent increase in maintenance costs. The dummy variable coefficient for a future renewal is significant at the 1 percent level, with a coefficient close to -0.16. Since it is a dummy variable, the elasticity is calculated as ($e^{\hat{\phi}_1}$ - 1), which gives -0.15. Hence, maintenance costs are reduced by approximately 15 percent in the year prior to a planned major renewal as defined in section 4.

The importance of the unobserved fixed effect can be measured as $\rho = \sigma_\alpha^2 / (\sigma_\alpha^2 + \sigma_\varepsilon^2)$ (Wooldridge, 2002). ρ is estimated to 0.88, i.e. almost 90 per cent of the variation is contributed to the variation in our unobserved effect.

The calculation of individual cost elasticities is based on expression (9), which is the derivative of the estimated cost function with respect to the output variable.[7] The standard error of the elasticity is computed using the Delta method (Greene, 2003, Appendix D.2.7).

$$\hat{\gamma}_{it}^{M} = \hat{\beta}_1 + (2 \cdot \hat{\beta}_2 \cdot \ln TGT_{it}) + (3 \cdot \hat{\beta}_3 \cdot (\ln TGT_{it})^2) \tag{9}$$

The mean cost elasticity with respect to output is estimated to 0.26, significant at the 5 percent level (standard error 0.13). A scatter plot of predicted elasticities is given in Figure 1.

Average costs (*AC*) are predicted costs divided by output kilometres at track section level (10). Track section specific marginal costs (*MC*) are calculated as the product between the output elasticity and the average cost (11).

$$AC_{it}^{M} = \frac{\hat{C}_{it}^{M}}{GTKM_{it}} \tag{10}$$

$$MC_{it}^{M} = \hat{\gamma}_{it}^{M} \cdot AC_{it}^{M} \tag{11}$$

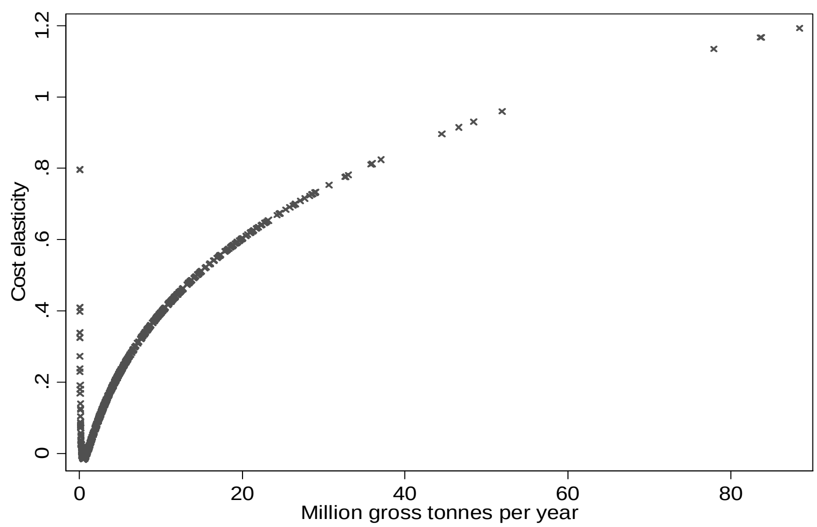

Figure 1. Maintenance cost elasticity with respect to output – Model I

If we adjust the marginal cost and estimate a mean value taking individual traffic levels into account, we get a weighted marginal cost (MC_w) for the entire network based on the traffic share per track section as in (12). This procedure generates at common marginal cost to all track sections and is revenue neutral compared to applying individual marginal costs to all track sections.

$$MC_{W}^{M} = \sum_{it} \left[MC_{it}^{M} \cdot \frac{TGKM_{it}}{\sum_{it} TGKM_{it}} \right] \tag{12}$$

The mean of the average cost per gross tonne kilometre is SEK 0.09, and marginal cost SEK 0.015. The weighted marginal cost is estimated to SEK 0.0070 per gross tonne kilometre (standard error 0.00048).

[7] This follows from the model specification using the logarithm of costs as dependent variable and logarithm of output as independent variable, known as a *log-log*, *double-log* or *log-linear* model (Gujarati, 1995).

5.1.2 Maintenance costs and lagged traffic - Model II

In the second model for maintenance costs, the effect of using lagged output as a covariate is analysed. We have also tried a model using both traffic volume in *t* and *t*-1, but with strong correlation between traffic over time, traffic in *t* is excluded from the model. The third-degree polynomial for output used in *Model I* is no longer significant and we reduce the model to a second-degree. Furthermore, the dummy for renewals in *t* + 2 and rail age are insignificant at the 10 percent level. Based on AIC and BIC, the final model is given in (13).

$$\ln C_{it}^{M} = \alpha_i + \beta_1 \ln TGT_{it-1} + \beta_2 (\ln TGT_{it-1})^2 + \phi_1 D_{it,1}^{R} + \varepsilon_{it} \tag{13}$$

One year of observations is lost when introducing lagged output to the model, and the sample size is reduced to 559 observations. The model results are given in Table 3.
The *F* test indicates that we have a significant model and all coefficients have expected signs. The mean output elasticity is 0.65 (standard error 0.161), significantly positive at the 1 percent level and substantially higher than in *Model I*. The elasticity for a future renewal is at -0.16 for *t* + 1, significantly negative at the 1 percent level. The cost elasticity with respect to output is increasing at a decreasing rate (figure 2), and exceeds 1 at 17 million gross tonnes per year. The economies of density are then exhausted, i.e. costs increase more than proportionally to increased traffic (Caves et al., 1985).
Given by the high output elasticity, marginal cost estimates are much higher in this model, with a weighted estimate of SEK 0.016 (standard error 0.0009) per gross tonne kilometre. This is more than twice as high as the *Model I* estimate.

Table 3. Results from a FE model for infrastructure maintenance costs, lagged traffic variables and renewal dummy - *Model II*

Variable	Coefficient	(Robust S.E.)
ln TGT_{t-1}	-2.535231‡	(0.974259)
(ln TGT_{t-1})^2	0.106395‡	(0.034956)
Renewal$_{t+1}$	-0.173948‡	(0.054259)
	Observations = 559	Groups = 188
	F(3, 368) = 9.19	prob. > F = 0.0000
Correlation between unobserved effect and included covariates = -0.42		
σ_α = 1.001 σ_ε = 0.366 ρ = 0.880		

Legend: ‡ Significant at 1% level; † Significant at 5% level; * Significant at 10% level.

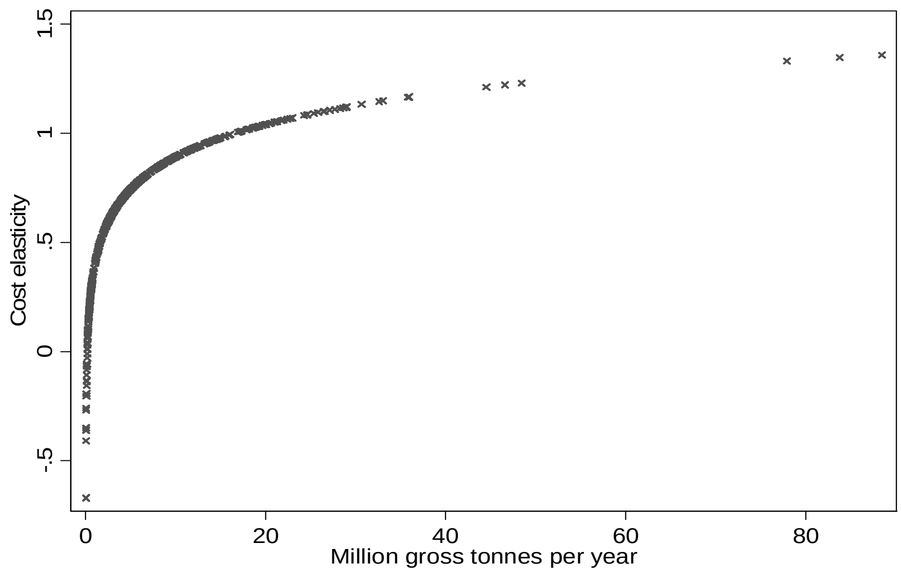

Figure 2. Maintenance cost elasticity with respect to output – Model II

5.1.3 Maintenance costs and lagged costs - Model III

The third model deals with the possibility of maintenance costs in *t*-1 affecting costs in *t*. The relatively short panel means that using a dynamic panel data specification for data from 1999 to 2002 will result in losing two full years of observations. The final sample consists of 371 observations.

The suggested model is given in (14) and builds on *Model II*. The difference is the inclusion of lagged costs as an explanatory variable, a dummy for 2002 to pick up systematic differences between 2002 and 2001[8], but also dropping the dummies for renewals based on AIC and BIC. Results from both one-step (*Model IIIa*) and two-step (*Model IIIb*) estimations are given in Table 4.

$$\ln C_{it}^{M} = \beta_1 \ln C_{it-1}^{M} + \beta_2 \ln TGT_{it-1} + \beta_3 (\ln TGT_{it-1})^2 + \phi_3 D_{it}^{2002} + \mu_i + \nu_{it} \quad (14)$$

The coefficient for our lagged cost variable is negative and significant from zero at the 1 percent level in *Model IIIa*. We notice a strong negative relationship between the first-difference in costs between *t*-1 and *t*. A 10 percent increase (reduction) in maintenance costs in *t*-1 generates a 5.6 percent cost reduction (increase) in *t*. This supports the hypothesis that costs are oscillating around a mean over time to keep the track in steady-state. Since the estimate of $|\beta_1| < 1$, we have a stationary process (Vandaele, 1983).

[8] The inclusion of time dummies is suggested by Roodman (2006) as a means of justifying the assumption of zero correlation across individual residuals in dynamic panel data models.

Table 4. Results from 1-step and 2-step Arellano & Bond dynamic panel data estimators for infrastructure maintenance costs - *Model IIIa* and *IIIb*

Variable	**Arellano & Bond 1-step**		**Arellano & Bond 2-step**	
	Coefficient	**(S.E.)**	**Coefficient**	**(S.E.)**
ln CM_{t-1}	-0.530707‡	(0.164266)	-0.596926‡	(0.206025)
ln TGT_{t-1}	-1.624755†	(0.666546)	-1.714501‡	(0.568782)
(ln TGT_{t-1})^2	0.065531†	(0.026626)	0.067006‡	(0.023551)
Year 2002	0.253046‡	(0.033417)	0.222457‡	(0.046353)
Observations		371		371
Groups		186		186
Wald χ^2 (4 df)		48.53		33.79
Sargan's χ^2 (2 df)		8.70; $p > \chi^2 = 0.013$		3.10; $p > \chi^2 = 0.212$
Autocov. Order 1		-1.13; $p > z = 0.258$		-0.67; $p > z = 0.505$
Autocov. Order 2		-		-

Legend: ‡ Significant at 1% level; † Significant at 5% level; * Significant at 10% level.

There is a risk of an over-identified specification when using the Arellano and Bond estimator, i.e. the number of instruments exceeds the included regressors. Testing for over-identifying restrictions is a way of controlling the validity of the included instruments. There is though a possibility that a rejection of the instruments comes from violating the conditions of homoscedasticity, rather than weak instruments (StataCorp, 2005). A solution is then to use a two-step estimator for model validation, but a one-step estimator for parameter inference. Furthermore, second-order autocorrelation in the residuals would lead to inconsistent estimates and needs to be tested for.

We maintain the null hypothesis of no first-order autocorrelation in the differenced residuals in both *Model IIIa* and *IIIb*. The short panel makes the test for second-order autocorrelation impossible to perform as the residuals in *t* and *t*-2 have no observations in common.

Using the Sargan test for over-identifying restrictions, we also maintain the null hypothesis that the instruments are valid based on *Model IIIb*. In *Model IIIa* we reject the validity of the instruments, but base our inference on individual coefficients from this model as suggested by StataCorp (2005).[9]

The dynamic model gives us the possibility to calculate both short-run and long-run cost elasticities with respect to output. The short-run elasticity is calculated as in the previous sections, but the formula for the long-run elasticity is slightly different. Based on our specification in (14), expression (15) gives us the long-run elasticity for infrastructure maintenance costs with respect to gross tonnes, with $\hat{\beta}_1$ being the estimated coefficient for our lagged dependent variable, and $\hat{\beta}_2$ and $\hat{\beta}_3$ our estimated output coefficients. The coefficient for our lagged dependent variable simply works as a scale factor between short-run and long-run effects.

$$\hat{\gamma}_{LR}^{M} = \frac{1}{(1-\hat{\beta}_1)} \cdot \left[\hat{\beta}_2 + 2 \cdot \hat{\beta}_3 \cdot (\ln TGT_{it-1})^2\right] \tag{15}$$

The short-run cost elasticity point estimate is calculated to 0.34 (standard error 0.193), significantly positive at the 10 percent level. The long-run elasticity is lower than the short-run elasticity due to the negative sign of the coefficient for our lagged dependent variable. A traditional definition of short-run and long-run cost elasticities is that in the short-run, the production technology is given, while in the long-run it is not. In our case, long-run is rather the

[9] Note that it is straightforward to interpret these coefficients in the same way as for the static fixed effects models, even if we use differences in the estimation stage to eliminate individual specific effects (see Baltagi, 2005).

effect from including the level of maintenance undertaken in a previous time period. A marginal change in traffic in *t*-1 will affect the level of maintenance in *t*-1, which in turn will affect the level of maintenance in *t*. This combined effect is captured in our long-run estimate. The point estimate of the long-run elasticity is 0.22 (standard error 0.132), but only significant from zero at the 10 percent level. Predicted elasticities are given in Figure 4.

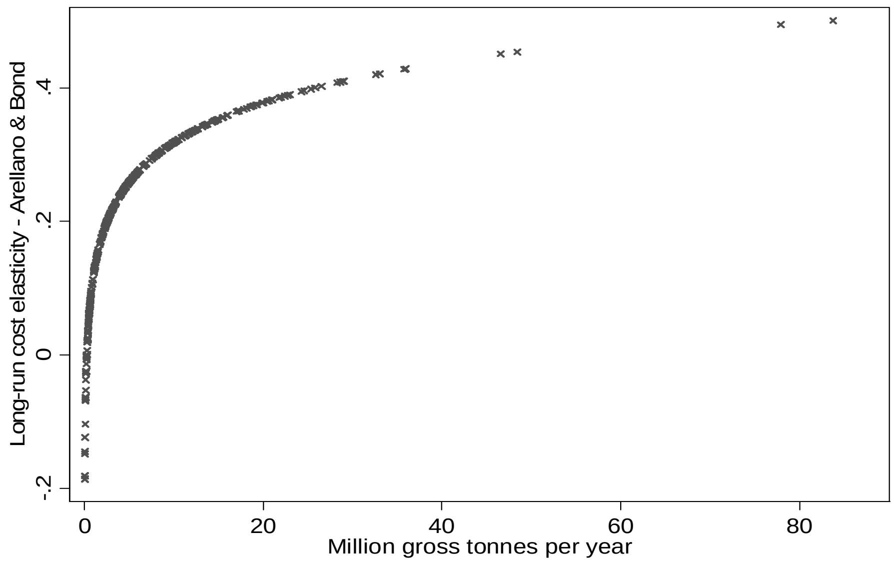

Figure 3. Long-run maintenance cost elasticity with respect to output – Model IIIa

To predict costs and calculate marginal costs from *Model IIIa*, we need to look at the actual model that is estimated.

$$\begin{aligned}(\ln C_{it}^{M} - \ln C_{it-1}^{M}) &= \hat{\beta}_1(\ln C_{it-1}^{M} - \ln C_{it-2}^{M}) + \hat{\beta}_2(\ln TGT_{it-1} - \ln TGT_{it-2}) + \\ &\hat{\beta}_3((\ln TGT_{it-1})^2 - (\ln TGT_{it-2})^2) + \hat{\phi}_3(D_{it}^{2002} - D_{it-1}^{2002}) + (\hat{v}_{it} - \hat{v}_{it-1})\end{aligned} \tag{16}$$

Rearranging (16) to get $\ln \hat{C}_{it}^{M}$ on the left-hand side and replacing $\hat{\beta}_1$ with our estimated coefficient, gives (17), which is used for prediction.

$$\ln \hat{C}_{it}^{M} = 0.469 \ln C_{it-1}^{M} + 0.531 \ln C_{it-2}^{M} + \cdots + (\hat{v}_{it} - \hat{v}_{it-1}) \tag{17}$$

The terms left out in the middle are the first-differences of our included variables multiplied by our estimated coefficients. The estimated, weighted short-run marginal cost is SEK 0.0092 (standard error 0.00064) per gross tonne kilometre, which is 30 percent higher than in *Model I*. The long-run estimate on the other hand is SEK 0.0060 (standard error 0.00042) per gross tonne kilometre, which is 15 percent below the *Model I* estimate.

5.2 *Infrastructure operation costs*

In the previous section, we found maintenance costs being reduced in the year prior to a major renewal when using static fixed effects models. In this sub-section, a model for infrastructure operation costs in the presence of anticipated future renewals is explored to check if this category follows the same pattern. This model is an extension of the suggested static model in Andersson (2007a) and fixed effects at track section level are assumed.

Model IV is for infrastructure operation (or short-term maintenance) costs using a third-degree polynomial for the natural logarithm of trains (*TT*) and dummy variables for future renewals

($D_{it,m}^{R}$). A model with dummy variables for renewals in both *t*+1 and *t*+2 has been tested, but again the coefficient for renewals in *t*+2 is insignificant and excluded based on Akaike's Information Criterion. The final specification with one dummy variable for major renewals is given in expression (18). Fixed effects (FE) at track section level are captured in α_i, and ε_{it} is the homoscedastic error term with zero mean. The estimates of the reduced model are given in Table 5.

$$\ln C_{it}^{O} = \alpha_i + \beta_1 \ln TT_{it} + \beta_2 (\ln TT_{it})^2 + \beta_3 (\ln TT_{it})^3 + \phi_1 D_{it,1}^{R} + \varepsilon_{it} \quad (18)$$

Table 5. Results from a FE model for infrastructure operation costs with renewal dummy - *Model IV*

Variable	Coefficient	(Robust S.E.)
ln *TT*	5.842519†	(2.302988)
(ln *TT*)^2	-0.949180‡	(0.303124)
(ln *TT*)^3	0.045129‡	(0.013043)
Renewal$_{t+1}$	-0.349163‡	(0.129940)
	Observations = 749	Groups = 190
	F(4, 555) = 6.10	prob. > F = 0.0008
Correlation between unobserved effect and included covariates = -0.60		
σ_α = 1.828 σ_ε = 0.632 ρ = 0.890		

Legend: ‡ Significant at 1% level; † Significant at 5% level; * Significant at 10% level.

The overall model is significant at the 1 percent level based on the *F* test. There is a strong correlation between the unobserved effect and our included covariates (-0.6). The importance of the unobserved fixed effect, ρ, is estimated to 0.89, i.e. almost 90 per cent of the variation is contributed to the variation in our unobserved effect. We also reject the model in Andersson (2007a) based on AIC.

The negative point estimate of the output elasticity looks doubtful at first sight (-0.036 (standard error 0.19)), but if we look at individual estimates, they range from negative to positive (figure 1). In fact, low volume tracks have negative elasticities, but at 13,000 trains per year (or 35 trains per day) the sign shifts from negative to positive. This means that additional trains contribute positively (reduce costs) to winter maintenance up to a certain level, but this positive effect is exhausted as volumes exceed this threshold. This finding is in line with a commonly held view in the Swedish railway industry, that trains help to sweep the snow of the track. Furthermore, diseconomies of density appear at 45,000 trains per year (or 120 trains per day).

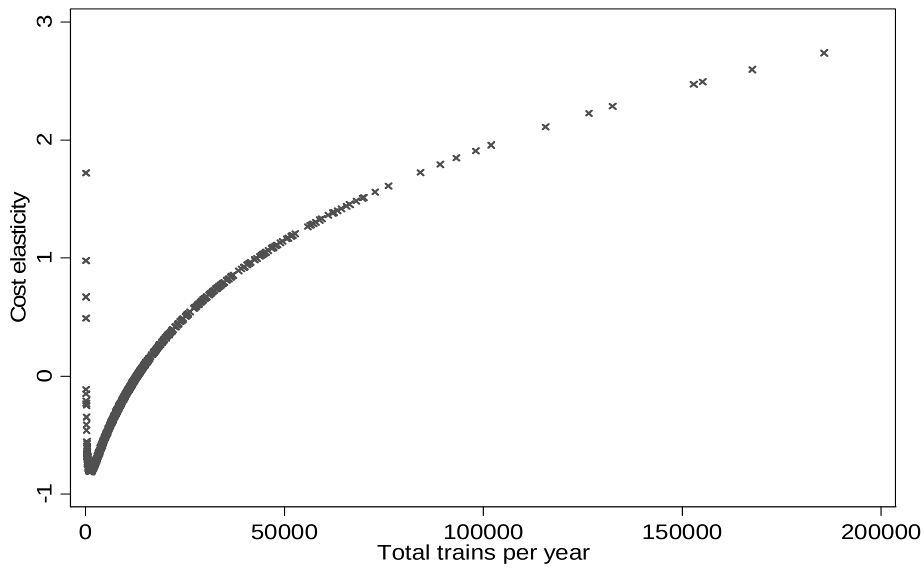

Figure 4. Infrastructure operation cost elasticity with respect to output – Model IV

The coefficient for future renewals on infrastructure operation costs is -0.349 (standard error 0.130) and significant at the 5 percent level. Since it is a dummy variable, the effect from a planned renewal in t+1 is an infrastructure operation cost reduction by 29 percent in t.
Average costs, marginal costs and weighted marginal costs are calculated using expressions (10) – (12), with train kilometres as output measure.
The mean of the average cost is SEK 7.28 (standard error 1.263) per train kilometre, while the mean of the marginal cost is negative at SEK -3.42 (standard error 0.938). This follows from high average costs and negative elasticities on track sections with low volumes that contribute heavily to the point estimate. The weight-adjusted marginal cost point estimate is positive at SEK 0.089 (standard error 0.077) per train kilometre, but insignificantly different from zero at the 10 percent level.

6. Discussion and conclusions

In this paper we have estimated econometric models for railway infrastructure costs in Sweden and tested the robustness of previous marginal cost estimates by introducing both lags and leads of dependent and independent variables in our cost functions. The main results from section 5 are given in Tables 6 and 7, together with previous estimates using the same data set (Andersson, 2006 and 2007a).

Table 6. Maintenance costs - main results

Method	**Output variable**	**Output elasticity***	**Renewal elasticity****	**Marginal cost*****
POLS (Andersson, 2006)	Gross tonnes	0.21	n.a.	0.0031
FE (Andersson, 2007a)	Gross tonnes	0.27	n.a.	0.0073
FE + Ren. Dummy (*Model I*)	Gross tonnes	0.26	-0.15	0.0070
FE + Lagged traffic (*Model II*)	Gross tonnes	0.65	-0.16	0.0164
GMM Short-run (*Model IIIa*)	Gross tonnes	0.34	n.a.	0.0092
GMM Long-run (*Model IIIb*)	Gross tonnes	0.22	n.a.	0.0060

* Mean cost elasticity with respect to output

** Elasticity with respect to major renewal in t+1
*** Marginal cost expressed as a weighted network mean in Swedish Kronor per output kilometre

Table 7. Infrastructure operation costs - main results

Method	Output variable	Output elasticity*	Renewal elasticity**	Marginal cost***
POLS (Andersson, 2006)	Trains	0.37	n.a.	0.476
FE (Andersson, 2007a)	Trains	-0.01	n.a.	0.127
FE + Ren. Dummy (*Model IV*)	Trains	-0.04	-0.29	0.089

* Mean cost elasticity with respect to output
** Elasticity with respect to major renewal in t+1
*** Marginal cost expressed as a weighted network mean in Swedish Kronor per output kilometre

The first analysis concerns the effect on costs from planned future renewals and both maintenance (*Model I*) and infrastructure operation (*Model IV*) costs are reduced a year prior to a major renewal. This confirms the informal forward-looking management strategy at Banverket, aiming at track maintenance cost minimisation. A 15 percent reduction in maintenance costs together with a 30 percent reduction in operation costs is found in this study. The magnitude of these reductions has been previously unknown. The effect on previous marginal cost estimates is not so large though for maintenance, but rather more for infrastructure operation costs.

The second analysis deals with the potential time delay between observed traffic volumes and maintenance activities. When introducing a one-year lag structure in our explanatory output variable, we observe a substantially higher cost elasticity with respect to output and marginal cost estimate compared to previous model estimates. The model picks up a significant relationship between costs in t and traffic in t - 1, but it is difficult to draw any firm conclusions from this. The reason is twofold; we lose a full year of observations, which in this case is around 25 percent of the data, and there is a high correlation between traffic in t and t - 1. The fact that traffic in t becomes insignificant in the model, when traffic in t - 1 is included, tells us something, but it is difficult to separate the dynamic hypothesis from the effect from the reduced sample and the correlation in output volumes. A longer time-series for each track section (a wider panel) is needed for this analysis to be more reliable, given the size of the difference in elasticities in *Model I* and *Model II*.

The third analysis focuses on lagged maintenance affecting current maintenance, and it is possible to estimate a dynamic panel data model for maintenance costs for this purpose. The short-run and long-run elasticities and marginal cost estimates are not too far away from what is estimated in Andersson (2007a), or from the estimates in *Model I*. We find support for a stationary and cyclic spending pattern for maintenance, with a negative first-order autoregressive coefficient of -0.53, i.e. maintenance in t - 1 has an impact on maintenance in t. It also shows that maintenance costs seem to be balanced around some level that keeps the track in steady-state.

So what can we learn from this analysis? The key finding is that there are dynamic aspects that affect the cost structure of the Swedish railway network and they are important to explore further in the future. There is a link between renewals, maintenance and infrastructure operation, which needs to be addressed in rail infrastructure cost modelling and this recommendation is given to all rail infrastructure managers in Europe. Analysing annual maintenance costs can be misleading as we find evidence of cyclic, oscillating variation in this cost category over time. The fact that costs are reduced prior to a renewal can be used in the budget allocation process, when forthcoming renewals are known.

On the short side, the available panel data covers a time window too short for us to draw any strong conclusions. The data set needs to be extended in time in order for us to explore optimal lag structures of both dependent and independent variables. There are some positive signs in that direction in Sweden as data collection and analysis have been given priority at Banverket. Combining the data set used in this study, with more recent data as well as data from the mid 1990's might generate a panel that covers up to 15 years. This would open up possibilities for improved dynamic analyses. Also, deferring maintenance and infrastructure operation costs might lead to reduced ride quality, delays and speed restrictions. Therefore, this informal strategy could be economically inefficient. This analysis is suggested for the future.

A recommendation to pricing policy-makers would be to focus on the results from *Model I* and *Model IV* in combination with the results in Andersson (2007). These analyses indicate that the marginal cost for infrastructure operation is around SEK 0.10 per train kilometre on average. The equivalence for infrastructure maintenance is SEK 0.0070 per gross tonne kilometre. If we look at the potential for cost recovery, a constant challenge for the transportation industry (Button, 2005), marginal cost pricing leaves a large part of the rail infrastructure costs uncovered. Cost recovery is defined as the ratio between marginal and average costs and the current rail infrastructure cost recovery rate in Sweden is as low as 5 percent. Scandinavian countries are also considered having the lowest wear and tear charges in Europe, which can explain the low cost recovery rate (Nash, 2005). With SEK 2.7 billion spent on railway maintenance annually, charging SEK 0.0070 per gross tonne kilometre would generate an income of SEK 455 million per year.[10] Adding a charge for infrastructure operation of SEK 0.10 per train kilometre would bring in just over 10 million per year. All in all, this would lead to a cost recovery rate of 17 percent based on a marginal cost pricing principle, given no effects on the demand for train operations from the increased charges. Recovering at least marginal cost is a prioritised issue as under-pricing will lead to over-utilisation of the infrastructure. In the long run, this will place an unwarranted financial strain on the government to solve capacity bottlenecks.

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[10] Total traffic volume in gross tonne kilometres is approximately 65 billion per year. The equivalence for train kilometres is 120 million.

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