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EMPIRICAL ESSAYS ON RAILWAY INFRASTRUCTURE COSTS IN SWEDEN

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Abstract

The subject of this thesis concerns pricing the use of transport infrastructure. We are empirically investigating the relationship between railway traffic volumes and infrastructure management costs. More specifically, we are interested in estimating the change in infrastructure management costs from marginal variations in traffic volumes, i.e. to estimate the marginal cost of railway infrastructure wear and tear. Both Europe and Sweden have moved towards a marginal cost based transport pricing policy, thus driving the need for more empirical work on rail infrastructure costs to underpin the level of a wear and tear charge. The thesis consists of five papers. In paper I, the data situation for planning railway maintenance and renewal is surveyed internationally. The survey indicates that most infrastructure managers are still in the data gathering phase, rather than ready to use modern computerised planning tools to make sound decisions in the field of maintenance and renewal. In paper II, we investigate the data situation for infrastructure cost analysis in Sweden. A panel data set that consists of cost, traffic and infrastructure information is created. The data covers 1999-2002 and contains almost 190 annual observations. Three main cost categories are identified; infrastructure operation, maintenance and renewal. This data is used for estimations of cost functions in paper II, III and V. Econometric techniques are applied for this purpose, with several different model specifications. In paper II, the method of pooled ordinary least squares (POLS) is applied. In paper III, we turn to unobserved effects models to exploit data heterogeneity. Finally in paper V, a dynamic generalised method of moments estimator is used to explore a potential dynamic cost dependency. The main findings are that the POLS approach, which has been used in similar studies in Europe recently, is rejected in favour of fixed effects estimation for this data. Furthermore, we also reject the idea of regression analysis to capture marginal rail renewal costs. In paper IV, we suggest an analytical expression combined with survival analysis of rail ages to estimate marginal renewal costs. We derive elasticities with respect to output as well as marginal costs for the different cost categories, and find that the current charge for wear and tear in Sweden is well below these new estimates. This opens up for increased, marginal cost based rail infrastructure wear and tear charges, which would reduce the financial burden on Swedish tax-payers.

Keywords: Railways, Infrastructure, Marginal Costs, Maintenance, Renewal, Econometrics, Panel Data, Survival Analysis

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Danholn, May 2007

Mats Andersson

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I, Andersson, M., Murray, M., Ferreira, L. and Lake, N., 2004. Collection and Use of Railway Track Performance and Maintenance Data. *New Horizons for Rail - Proceedings of CORE (Conference On Railway Engineering) 2004*, Railway Technical Society of Australasia, June 20-23, Darwin, Australia.

II, Andersson, M., 2006. Marginal Cost Pricing of Railway Infrastructure Operation, Maintenance and Renewal in Sweden: From Policy to Practice Through Existing Data. *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1943*, Transportation Research Board of the National Academies, Washington, D.C., 1-11.

III, Andersson, M., 2007. Fixed Effects Estimation of Marginal Railway Infrastructure Costs in Sweden.

IV, Andersson, M., 2007. Marginal Railway Renewal Costs: A Survival Data Approach.

V, Andersson, M., 2007. Marginal Railway Infrastructure Costs in a Dynamic Context.

I am grateful to the Railway Technical Society of Australasia (I) and the Transportation Research Board (II) for permission to include previously published papers in this thesis.

1. The Agenda for Railway Infrastructure Cost Analysis

The subject of this thesis concerns pricing the use of transport infrastructure. We are empirically investigating the relationship between railway traffic volumes and infrastructure management costs. More specifically, we are interested in estimating the change in infrastructure management costs from marginal variations in traffic volumes, i.e. to estimate the marginal cost of railway infrastructure wear and tear.

Sweden has a long tradition of public funding of transport infrastructure through general taxation of incomes, goods and services. Pricing principles have changed over the years, but the last decade has seen marginal cost pricing as a cornerstone in Swedish transport policy (Regeringen, 1998; Regeringen, 2006). At the same time, the idea of marginal cost pricing has also been put forward in a number of transport and railway policy documents by the European Community. A review of the European policy development is found in Nash and Matthews (2002).

Sweden recently changed its railway legislation (Riksdagen, 2004) to implement recommendations outlined in several directives from the European Community (European Parliament, 2001a-d). Directive 2001/14/EC addresses charging for the use of railway infrastructure, but is not specific on which pricing regime to use. Charges should give railway operators opportunities to "make rational decisions" (European Parliament, 2001c, Para. 35) and "be set at the cost that is directly incurred as a result of a train service" (European Parliament, 2001c, Para. 38). This is close to stating that prices should equal marginal costs, but the European Parliament acknowledges the different policies on cost recovery in member states by allowing pricing above marginal cost through mark-ups.

A major change in the Swedish railway sector because of the new legislation was the establishment of the Swedish Rail Agency (Järnvägsstyrelsen) in July 2004 to serve as a regulatory body. At the same time, the Swedish National Rail Administration (Banverket) was given the responsibility of setting access fees for the national rail network, a duty previously held by the Swedish government. The introduction of a railway regulator gave train operators the possibility to question the pricing scheme and capacity allocation decided by Banverket. Therefore, the need for rigorously based marginal cost estimates has increased.

Banverket has collected around SEK 500 Million annually in access charges from train operating companies over the last years (Banverket, 2007)[1]. Approximately 60 percent of total revenue from access charges stems from the *track charge*, which is based on costs for infrastructure maintenance. The remainder comes from charges for accidents, air pollution, freight train marshalling, and traffic information. This shows the importance of correctly charging for infrastructure wear and tear. Still, the revenues from the track charge are well below total infrastructure management costs as can be expected in an industry with increasing returns to scale (Nash, 2003a). There is also increasing pressure on Banverket by the Swedish Ministry of Finance to review its pricing scheme to reduce the tax-payers burden for the national rail network. In a review of European rail infrastructure charges (Nash, 2005), Sweden was found to have the lowest charges among most European countries. This was explained by the Swedish short-run marginal cost pricing policy, but it was emphasised that the failure to charge for rail renewals may result in actually pricing below marginal cost.

Thus, there is a need for more empirical work on rail infrastructure costs to underpin the level of a wear and tear charge, which is the focus of this thesis. By using a variety of estimation techniques and model specifications, we contribute to current knowledge and provide a platform for future research to build on.

[1] The exchange rate from Swedish Kronor (SEK) to Euro (EUR) is SEK 9.23/EUR and from Swedish Kronor to US Dollar (USD) is SEK 6.78/USD (April 25, 2007).

2. Economic Theory and Marginal Cost Pricing

Textbooks in microeconomics demonstrate the benefits of marginal cost pricing to maximise social welfare. We also know that in industries operating under falling average costs, marginal cost pricing will lead to insufficient funding to cover total costs. The railway industry, with its high fixed costs, is considered such an industry. Therefore, railways in most countries in the world would operate with a loss under a marginal cost pricing rule unless the network is fully utilised.

The literature discussing the pros and cons of marginal cost pricing of public utilities has a long history, which cannot be fully justified in this introduction. An influential paper by Harold Hotelling, entitled “The General Welfare in Relation to Problems of Taxation and of Railway and Utility Rates” appears in *Econometrica* already in 1938. Hotelling shows that pricing at marginal cost and covering fixed costs through a general tax system, will lead to welfare maximisation.

Hotelling’s article formed a consensus around marginal cost pricing for a while, but Coase (1970) objects to the idea of marginal cost pricing and lists several weaknesses in the approach. Avoiding the importance of eliciting the willingness to pay for the full cost for goods and services as well as excluding the cost of increased taxation are, among others, arguments put forward against marginal cost pricing.

Kessides and Willig (1995) call for a sound access charging policy as one part of the restructuring of the railway industry. They point out that marginal cost pricing in the railway sector will inevitably lead to financial deficits from substantial fixed costs, and therefore suggest a pricing policy based on so called Ramsey prices. Ramsey prices distribute fixed costs among a railway’s services based on elasticities of demand. If demand for a particular service is sensitive to price changes, pricing above marginal cost will lead to a substantial drop in demand. Conversely, if demand for another service is insensitive to a price change, pricing above marginal cost will not lead to any significant reduction in demand. The idea behind Ramsey prices is to identify these demand elasticities, and adjust the efficient prices with the inverse of the elasticities of demand for all services to cover for fixed costs.

In a more recent review, Freebairn (1998) discusses the pros and cons of various access pricing regimes related to rail infrastructure. Regimes based on marginal cost, average cost, two-part tariffs and Ramsey prices are addressed and he overall favours marginal costs with an allowance for a mark-up. This mark-up should relate to the social cost of taxation (or the marginal cost of public funds), which is suggested by Baumol and Bradford (1970). Still, financial deficits are unlikely to be eliminated (Preston, 2002).

The issue of pricing cannot be viewed independently from an infrastructure management policy. Pricing at marginal cost at track section level needs to be linked to a policy where rail infrastructure operation, maintenance, renewal and investments are based on social cost-benefit analysis without a budget constraint (Hotelling, 1938). The situation in most railway organisations is most likely the opposite, and under-investment subsequently leads to higher than optimal marginal costs. This fact can be used as an argument for a flat rate rather than differentiated rates over the network, but is also a case for pricing below marginal cost.

Another aspect that needs to be addressed is the pricing of competitive modes. Rail transport is exposed to competition from road, air and sea transport in a number of destination pairs. The degree of competition will differ depending on distance, prices, quality, type of goods or service and more, which makes it a difficult issue to handle. If a mode on the transport market is priced too low compared to its true social costs, this will distort the entire transport market if other modes have to bear their true costs. It can therefore be an argument for pricing competitive modes below marginal cost to offer fair competition on the entire transport market (Nilsson, 1992).

Critique against the adoption of marginal cost pricing within the European Community is given in Rothengatter (2003), who lists nine different draw-backs from marginal cost pricing. He points out that marginal cost pricing has a static view that ignores equity issues, land-use impacts and dynamic behaviour. Furthermore, marginal costs are difficult to measure and the idea relies on the government as a good manager. Finally, marginal cost pricing would not lead to internalisation of external costs and would be financially insufficient.

Nash (2003a) responds to these arguments by recognising their existence, but advocates that a rejection of *measuring* marginal costs will not help society to come to terms with current pricing problems and transport system inefficiencies. In fact, most of the remedies to the problems listed by Rothengatter (2003) use marginal cost estimates as a starting point. Knowledge of marginal costs is therefore fundamental to rail infrastructure managers in light of the transport policy in Sweden and Europe. Thus, research that addresses the estimation of marginal cost in transportation infrastructure is highly motivated.

3. Estimating Railway Infrastructure Cost Functions

Economists have been interested in the cost structure of railway organisations for a long time. Borts (1954) and Waters (1985) refer to work done in the late 19th century on the subject. Actual cost function estimation using railway data has a history of well over 50 years now, but the academic literature is mainly dominated by US studies based on time-series at firm-level, focusing on issues like productivity, economies of scale, scope and density, and capacity utilisation in the US freight market (c.f. Borts, 1960; Griliches, 1972; Keeler, 1974; Brown et al., 1979; Caves, Christensen and Swanson, 1980; Braeutigam et al., 1982; Oum and Waters, 1996). The majority of these studies are driven by a regulatory interest in the US rail market. If there is evidence of economies in some form, there is a need for regulatory intervention. Early studies indicate economies of scale in the railway sector, but with better econometric estimation techniques, economies of scale proved more or less non-existent. Differences in costs between organisations could rather be traced to issues related to capacity use, which is known as economies of density (Caves et al., 1985). Oum and Waters (1996) review the development of transportation cost functions and the railway studies referred to are dominated by constant returns to scale estimates. Recent studies related to maintenance costs for US railways using post-deregulation data are Bereskin (2000), who estimates marginal maintenance-of-way costs for a sample of US freight railways, and Bitzan (2003), who addresses the issue of cost effects from on-track competition in the US.

All US studies use some sort of aggregated firm data, whether a time-series for a specific firm or a cross-section of a number of firms. To our knowledge, there are no published cost studies involving disaggregated (or micro-level) network data from individual railway organisations in the US.

Another aspect of the US cost structure is the issue of allocation of joint costs. This has been subject to debate for almost 100 years (c.f. Haney, 1916). As there are a number of private railway organisations with regionally limited networks, they need access to competitors' tracks for the possibility to serve a larger area. This drives the need for allocating costs among the different users, and to separate fixed costs from costs that vary with output. This is basically an exercise of estimating marginal costs, but the few published cost allocation studies have rather used track maintenance planning models (Martland, 2001; Resor and Patel, 2002) for this purpose. One plausible explanation for this can be the lack of access to micro-level data in the US and that cost allocation is included in proprietary business agreements between private companies. Rail cost analysis is often hampered by lack of data and deregulation of the railway industry has in fact made the situation even worse on the aggregate US industry level (Oum and Waters, 1996).

Martland (2001) discusses the potential use of the maintenance planning model TRACS for allocation of track costs. TRACS was developed with financial support from the American Association of Railroads (AAR) in the early 1990's. He finds that a maintenance planning model may play an important role in cost allocation studies.

Resor and Patel (2002) use the TrackShare model developed by ZETA-TECH Associates, Inc., for allocating the maintenance costs for AMTRAK's north eastern corridor where a number of operators run train services, both freight and passenger. TrackShare is built on engineering factors and a systematic breakdown of costs and usage for US freight operator Conrail results in a significantly lower estimate than would have been the case using AMTRAK´s cost allocation method. Traffic dependency is not estimated in the model, but is rather built into it. Recent model applications have given approximately 50 % of all costs being dependent on traffic (Resor and Patel, 2002).

The use of micro-level data and the issue of marginal cost estimation have instead been a European affair emerging in 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, 2001c). 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, 2003b), finding best practices in member states (Thomas et al., 2003) and disseminating findings (Nash and Matthews, 2005).

The trend in Europe's railway sector is towards vertically separated rail sectors with multiple operating companies. This drives the need for a non-discriminatory pricing regime. As mentioned above, pricing at marginal social cost can be viewed as such and is also suggested from economic theory to optimally utilise an existing network.

In a review of European rail infrastructure charges, Nash (2005) lists a handful of empirical studies, with the majority never published in academic journals. Lack of data resulting from such events as mergers and acquisitions (eliminating sufficiently long time series) and a focus on day-to-day operations has often restricted micro-level analyses in the railway sector (ECMT, 2005). The lack of empirical studies using micro-level data is also confirmed by Lindberg (2006).

In fact, the only published study to date using micro-level data is a Swedish study by Johansson and Nilsson (2004). They apply a Translog type of cost function specification (Christensen et al., 1973) on Swedish railway data from 1994 to 1996 as well as data from Finland in 1997-1999. The suggested model for Sweden is based on a pooled data set of annual track sections (network links and nodes) with infrastructure maintenance costs as dependent variable. For Finland, the same approach is suggested, but data also includes renewal costs.

The approach taken by Johansson and Nilsson (2004) to use infrastructure costs as dependent variable, and traffic variables as well as infrastructure standard as independent variables has been used in most research to follow. Among recent unpublished work, Munduch et al. (2002) use three years of observations from the Austrian Railways. The data consist of track maintenance costs, traffic volumes in gross tonnes, and a rich set of infrastructure variables. In a preliminary paper by Gaudry and Quinet (2003), a very large data set for French railways in 1999 is used. They explore a variety of unrestricted generalised Box-Cox models to allocate maintenance costs to different traffic classes. Daljord (2003) estimate Cobb-Douglas and Translog functions on Norwegian maintenance cost data from 1999 to 2001, but his estimations suffer heavily from lack of data. Tervonen and Idström (2004) differ in their approach by a priori identifying fixed and variable cost groups in the accounts of the Finnish railways, and only analysing variable costs. The analysis is made on maintenance costs as well as an aggregate of maintenance and renewal. Marti and Neuenschwander (2006) estimate a model for maintenance cost data on the Swiss national network during 2003-2005. While the studies above make use of micro-level data (track sections), the study by Smith and Wheat (2006) used data from 53 maintenance delivery units for the Great British Network in 2005/06.

Considering the variation between the recent individual studies, the results are convergent in terms of cost elasticities with respect to output, when controlling for the cost base used in each study (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. This indicates significant economies of density from increasing output on a fixed track. These findings are in fact in line with what Borts (1954) finds in the literature written some 70-100 years ago, although they refer to scale economies in vertically integrated railway organisations in the US.

4. Methods

We have pointed out above that knowledge of marginal costs is essential to today's European railway administrations. Among the available methods to estimate the marginal costs, we will use an econometric approach. Econometrics is an application of statistical methods to economic data. To estimate a cost function, we build on the duality between production and costs under the assumption that costs are minimised for a given level of output and input of factor prices. We can describe the relationship between costs (*C*), output (*Q*) and prices (*P*) as $C = f(Q, P)$. For our analyses, we have reasons to believe that the spatial variation in factor prices, i.e. labour costs over the Swedish rail network is negligible. This idea was first suggested by Johansson and Nilsson (2004) with the argument that the Swedish labour market agreements are heavily regulated at a national level. Another reason is that the majority of the track work is done in-house by the Production Division of Banverket. We will therefore exclude the factor price vector *P* in our estimated cost functions and proceed with the assumption of equal factor prices over the network.

However, output is not the only factor that can influence the variation in costs over a rail network. As output varies over the network, so do the technical characteristics of the track, climate and managerial skills, which need to be controlled for. Thus, we will assume that there is a relationship between costs for infrastructure operation, maintenance and renewal (*C*), and the level of traffic (*Q*) given other characteristics of the infrastructure (*X*); $C = f(Q, X)$.

As a starting point, the logarithmic version of the classical multiple linear regression model is applied.

$$\ln C_{it} = \alpha + \sum_{j=1}^{n} \gamma_j \ln Q_{jit} + \sum_{k=1}^{m} \beta_k \ln X_{kit} + \varepsilon_{it} \qquad (1)$$

where C_{it} is the cost for observation i at time t, α the common intercept, γ_j and β_k the n and m partial regression coefficients, Q the measurements of output from the track in terms of traffic (trains, gross tonnes), X the input variables we want to control for (infrastructure, quality, climate etc) and ε_{it} the error term being independent with a constant variance and zero mean.

Over the years, this simple form has been extended to include non-linearities. A popular model for estimating a cost function with an unknown underlying functional form has been the Transcendental Logarithmic (Translog) model (Christensen et al., 1973) introduced to railway cost analysis by Brown et al. (1979). Following Brown et al., we can write the Translog function for n outputs and m inputs as

$$\begin{aligned} \ln C_{it} &= \alpha + \sum_{j=1}^{n} \beta_j \ln Q_{jit} + \sum_{k=1}^{m} \delta_k \ln X_{kit} + \sum_{j=1}^{n} \sum_{k=1}^{m} \gamma_{jk} \ln Q_{jit} \ln X_{kit} \\ &+ \frac{1}{2} \sum_{j=1}^{n} \sum_{k=1}^{n} \rho_{jk} \ln Q_{jit} \ln Q_{kit} + \frac{1}{2} \sum_{j=1}^{m} \sum_{k=1}^{m} \omega_{jk} \ln X_{jit} \ln X_{kit} + \varepsilon_{it} \end{aligned} \tag{2}$$

where C is cost, Q and X are outputs and inputs respectively for track section i at time t. The original Translog use prices as inputs, but here X represent the technical characteristics of the track. The advantage of the Translog is the few assumptions about the underlying cost structure that has to be made. The coefficients γ, ρ, and ω have the ability to capture interaction between inputs and outputs. The disadvantage of the Translog is the number of coefficients that has to be estimated, which drives a need for a large number of observations. As railway data in most cases is a scarcity, other solutions have been sought. A common solution is to use restricted versions of the Translog specification to save degrees of freedom (Johansson and Nilsson, 2004; Smith and Wheat, 2006); Marti and Neuenschwander, 2006).

We will follow this approach and explore higher-order terms for key variables when significant in the model, but exclude interaction terms.

The estimated cost functions are presented in papers II, III and V. In paper II, we apply the same method as Johansson and Nilsson (2004), i.e. pooled ordinary least squares (POLS). POLS means that we use standard ordinary least squares estimation on a sample that is drawn on different observations *i* in different time periods *t* (Wooldridge, 2002). By doing this, we assume that there is no correlation between our observed variables in time *t* and the error term in time *s*, if $t = s$. In fact, POLS allows for correlation between observed variables and the error term, when $t \neq s$.

In paper III, we introduce panel data estimators or more specifically fixed effects (FE) estimation. In this model, we require strict exogeneity between observed variables and our error terms, conditional on the unobserved (fixed) effect. The unobserved effect (*z*) can be anything from climate, managerial skills, quality or some technical characteristics that we cannot observe.

There are some crucial assumptions that must be made about the unobserved effect. Most importantly, it has to be time-invariant i.e. for the time window we observe, it cannot change. Furthermore, we have to clarify whether the unobserved effect is correlated or not with *Q* and/or *X*. Let **w** be a vector of *j* independent variables (*Q* and *X*) included in the model. If $Cov(w_j, z) = 0$, then it can be handled within the error term and give unbiased estimates of the parameters for **w** (random effects estimation). If $Cov(w_j, z) \neq 0$ for some *j*, we face severe problems if *z* is not handled separate from the error term. We will allow for our observed variables to be correlated with our unobserved effect (fixed effect estimation), which opens up for consistent estimation of our model parameters independent of how unobserved and observed variables are related. The price for this opportunity is that we cannot include any time-invariant variables in our FE model.

In paper V, the models in paper III are extended by introducing lagged independent and dependent variables in the vector of observed variables. Lagged independent variables pose no direct problems apart from reducing the sample size, but lagged dependent variables give rise to potential problems of autocorrelation; a systematic pattern in our residuals. A generalised method of moments (GMM) estimator by Arellano & Bond (1991) solves this by first-differencing the specified equation followed by an instrumental variable regression.

The method in paper IV differs from the econometric models used in paper II, III and V. We use an analytical expression for marginal railway track renewal costs, and estimate necessary model parameters by survival analysis of track segment ages. The approach is to compare two discounted cost streams, of infinite renewal cycles with different traffic volumes, to derive the marginal cost.

5. Data

Since the parliament decision to separate railway track ownership from operation in 1988, Banverket has developed a number of data systems to assist different levels of the organisation in the development and management of the Swedish national rail network. To date, no outright policy has been established for gathering or structuring data for maintenance and renewal planning, and cost analysis purposes. Therefore, we have to use various information sources when collecting data for our analysis.

The econometric approach chosen for paper II, III and V requires data to be at the lowest possible network level to provide a sufficient number of observations. The rail network consists of links (lines) that are formed from shorter segments of various quality and joined by nodes (stations, switches or meeting points). These links and nodes are labelled track sections. The minimum of information needed for each track section is cost, infrastructure and traffic data.

Data on infrastructure costs are obtained from Banverket's accounting system (Agresso). Track section data is collected for infrastructure operation, maintenance, and renewal from 1993 to 2005[2]. These cost categories can broadly be defined as short-, medium- and long-term actions. Detailed cost data is available only at the track section level and above.

The track information system (BIS) is a reference system for various applications at Banverket. It is used as an up-to-date system for describing the characteristics of the rail network. BIS is using the same track section numbers as Agresso, which makes the matching of infrastructure and cost data straightforward. The data in BIS is available at a lower level than track sections. For the econometric analyses, we have therefore aggregated this information to match the other data sources.

[2] Infrastructure operation costs are not available at track section level before 1999.

The Swedish train operation market is mainly dominated by three operators; SJ (passenger), Green Cargo (freight) and MTAB (freight) (Andersson, 2003). Since the separation of train operations from infrastructure management in 1988, Banverket has continued to rely on traffic data systems controlled and maintained by SJ and Green Cargo, which include their passenger and freight movements. This situation has caused some problems with the supply of traffic information for analysis purposes. As competition on the track has increased over time, the quality and importance of the SJ/Green Cargo databases have decreased. We have kindly been given permission by SJ, Green Cargo and MTAB to use their traffic information for this thesis work. Together with published time tables, and information from the remaining operators, we have constructed a traffic database for 1999 - 2002.

Missing data is an issue in both BIS and Agresso, but when reviewing the available data, it turns out that a lot of these problems are related to track sections not managed by Banverket or lacking traffic altogether. We therefore solve the problem of missing data by removing some track sections, and by using a stochastic single imputation technique for the remaining track sections with missing data. As we move to panel data estimation in papers III and V, the issue of missing data becomes of even less importance as these estimators handle the issue better than the POLS. For the survival analysis, missing data is no problem.

In 2003, the total network had more than 250 different track sections, but our final sample consists of 186 observations in 1999, 186 in 2000, 188 in 2001, and 189 in 2002. All in all, 749 observations are used for the econometric cost analyses.

In paper IV, the detailed information in BIS is used by analysing track segments rather than sections. Some 1 500 segments, that form the main network, are used for this analysis. Meeting points, marshalling yards and stations are excluded. By doing this, we are able to match our knowledge of traffic volumes on track sections from the econometric analysis, with the more detailed track segment information. Hence, this provides a more realistic representation of the flows on a segment, than including all segments.

6. Results

The thesis consists of five individual papers, which are summarised below and related in the following way. Paper I deals with the availability of railway data for maintenance and renewal planning. In paper II, data availability in Sweden for infrastructure operation, maintenance and renewal cost analysis is specifically addressed, and cost functions are estimated using pooled ordinary least squares. In paper III, individual heterogeneity is taken into account, and cost functions are estimated with a fixed effects panel data estimator. Paper IV takes an alternative approach to estimating marginal rail renewal costs using net present values and survival data modelling. Finally, paper V incorporates some dynamic aspects of the cost data, using both the fixed effects estimator and a dynamic generalised method of moments estimator.

6.1 Paper I - Collection and Use of Railway Track Performance and Maintenance Data

The first paper deals with data collection and utilisation in the railway industry for maintenance and renewal planning purposes, and is co-authored with Professor Luis Ferreira, Dr. Martin Murray and Dr. Neal Lake at Queensland University of Technology, Brisbane, Australia.

Restructuring of the railway sector is driving the need for high quality data for decision-making. Modern planning tools for maintenance and renewal are becoming available on the market, and to be able to use these tools, a substantial amount of data is often needed. Railway organisations often collect data for different purposes. As data collection and storage technology is enhanced, it is tempting to collect as much as possible. A well judged data collection strategy can, not only minimise costs in terms of collection and storage, maximise the benefits from data utilisation if the right type of data is collected at the right level of detail. Are railway organisations ready to use modern planning tools or will lack of data prevent them to move from project prioritisation based on personal experience to a systematic and computerised analysis?

An international survey on the subject was designed to find out what type of data is collected, method of collection, and how it is utilised in a sample of Australian and international railway organisations. The initial response from several railway organisations around the world was that providing this type of information required a substantial work effort from different parts of a railway organisation.

With the limited number of responses, no strong conclusions can be made, but the overall impression from the survey is that most infrastructure managers are still in the data gathering phase, rather than ready to use modern information technology to make sound decisions in the field of maintenance and renewal.

6.2 Paper II - Marginal Cost Pricing of Railway Infrastructure Operation, Maintenance and Renewal in Sweden: From Policy to Practice Through Existing Data

In this paper, Swedish railway infrastructure cost data is reviewed and analysed. Focus in the analysis is to estimate cost functions and derive marginal costs for wear and tear. A review of infrastructure, cost and traffic data is undertaken, which shows that an analysis of these combined categories can be done on data between 1999 and 2002. Lack of data before and after these years prevents us from extending the time window.

There are some issues with missing data, and we solve these using single imputation techniques, i.e. generate a complete data set by estimating values for observations with missing data based on stochastic regression analysis.

The method of POLS is used in the analysis phase and we estimate three cost functions each for infrastructure operation, maintenance as well as the aggregate of maintenance and renewal. The separation of infrastructure operation from maintenance and renewal is based on the nature of this cost category, which affects the choice of the appropriate output variable.

Infrastructure operation is short-term maintenance dominated by snow removal. These actions are necessary to perform irrespective of train weights. Hence, we use trains rather than gross tonnes to represent output for this cost category. Conversely, maintenance and renewal activities are more forward-looking and related to the long-term quality status of the track. These cost groups are both assumed to have a stronger link to the number of gross tonnes on the track.

The regression analyses include an output variable, technical features of the track, and a range of dummy variables to explain the variation in costs. All models include variables like track section length, switches, rail weight, stations and track districts apart from individual specific variables. The relationship between costs and traffic is our main interest and as we specify a logarithmic model, we can derive cost elasticities with respect to our output variables directly from the coefficient estimates. Main results are given in table 1.

Table 1. Main results from cost functions estimated by POLS

Cost category	**Output variable**	**Cost elasticity***	**Marginal cost****
Infrastructure operation	Trains	0.37	0.476
Maintenance	Gross tonnes	0.21	0.0031
Maintenance and Renewal	Gross tonnes	0.26	0.0055

* Mean cost elasticity

** Marginal cost expressed as a weighted network mean in Swedish Kronor per output kilometre

The elasticity measures the percentage change in costs from a percentage change in our output variable. Previous elasticity estimates for the aggregate of infrastructure operation and maintenance in Sweden are in line with these estimates. Finally, we conclude that a well-designed data collection strategy is essential in order to estimate marginal costs in the future, but there is no such strategy in place at Banverket.

6.3 Paper III - Fixed Effects Estimation of Marginal Railway Infrastructure Costs in Sweden

The method of POLS that we used in our regression analyses in paper II faces the potential problem of incorrect model specifications through omitted variables. Hence, cost relationships derived from such models may lead to biased estimates and conclusions.

Unobserved effects models can alleviate the omitted variables problem in a POLS regression. In this paper, we use fixed effects (FE) estimation to capture individual heterogeneity at the track section level. The rationale for the fixed effects model is that our main interest is on the relationship between costs and output. During the four years that we observe our data, technical characteristics (length etc.) are constant (time-invariant), which makes it easy to include them in a track section specific constant. Furthermore, the problem of multicollinearity between the technical variables that we encountered in paper II is solved as we no longer use these variables directly.

Table 2. Main results from cost functions estimated by FE

Cost category	**Output variable**	**Cost elasticity***	**Marginal cost****
Infrastructure operation	Trains	-0.01	0.127
Maintenance	Gross tonnes	0.27	0.0073
Maintenance and Renewal	Gross tonnes	0.13	-

* Mean cost elasticity
** Marginal cost expressed as a weighted network mean in Swedish Kronor per output kilometre

Using the same data set as in paper II, we estimate models assuming a time-invariant unobserved effect correlated with our included observed variables, i.e. FE models. When we incorporate the heterogeneity between track sections and estimate separate track specific constants to capture the fixed effect, we derive the following cost elasticities and marginal costs (table 2).

We find that the mean elasticity of infrastructure operation costs is insignificantly different from zero, but track section estimates range from negative to positive with increased output. This supports the idea that there are positive effects in terms of reduced costs for snow removal from train passages. However, this positive effect is exhausted around 12 000 trains per year, and as volumes increase there is a positive elasticity of cost with respect to trains.

The maintenance cost elasticity and marginal cost are higher than the POLS estimates in paper II. For the aggregate of maintenance and renewals, we estimate a cost elasticity that is insignificantly different from zero, which is difficult to justify on theoretical grounds. Still, the alternative specifications of POLS and random effects (RE) are rejected for all three cost categories, and we therefore question the inclusion of renewal costs in the econometric approach.

Switching from POLS to FE estimation removes potential omitted variable bias and multicollinearity between infrastructure variables, but with the drawback that we cannot make inference on the cost relationship for individual characteristics like switches, track lengths, organisational units etc.

6.4 Paper IV - Marginal Railway Renewal Costs: A Survival Data Approach

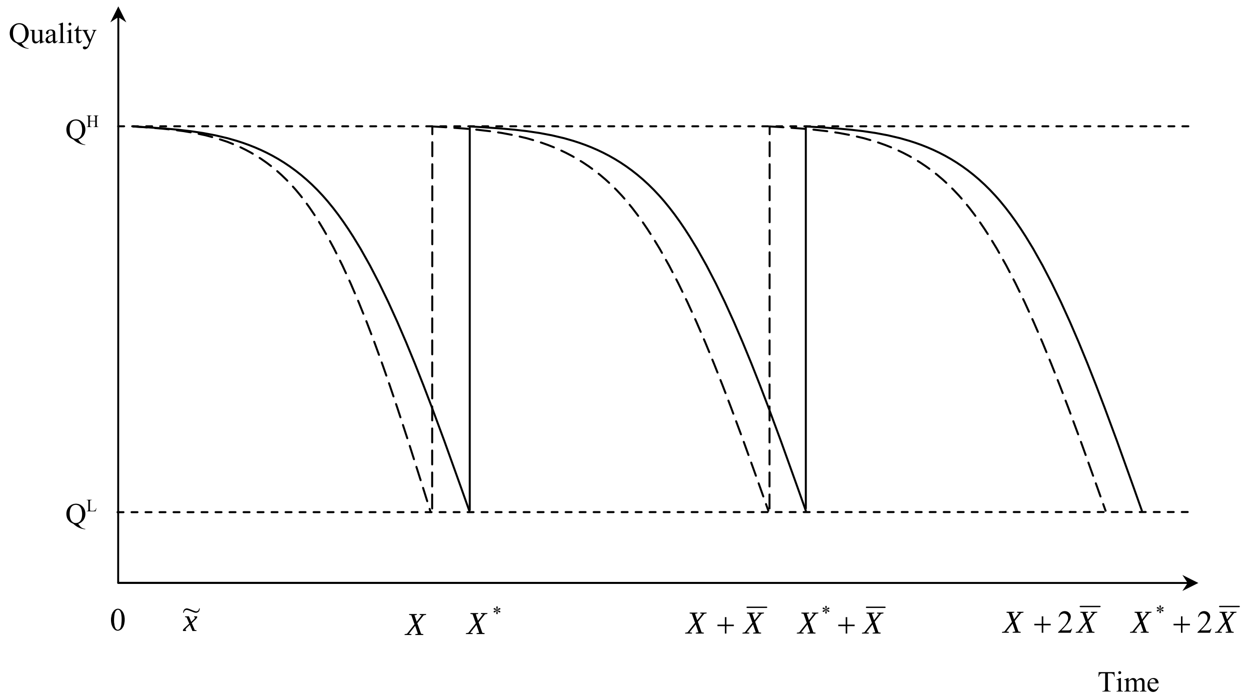
The problems that we faced in our fixed effect estimation of maintenance and renewal costs in paper III indicate that we need a different approach to modelling the marginal cost of rail renewal. In this paper, an analytical expression for marginal rail renewal costs is combined with survival modelling to identify necessary model parameters.

A censored flow sample of Swedish railway track segments is used to estimate Weibull survival models on approximately 1 500 observations of the main railway network.

Consider a model where the track initially has a quality of Q^H (figure 1). Traffic volumes reduce this quality over time and a renewal of the track is justified at X^* with quality Q^L, when the initial quality level Q^H is restored. Assuming constant traffic flows, this cycle is repeated into infinity with all future renewal intervals being of length $\overline{X}$.

The reduction in quality over time comes from track deterioration and is associated with a railway track management cost, discounted to a given reference year. The idea behind the marginal cost calculation is that a marginal increase in traffic is introduced in time period $\tilde{x}$. This shortens the first renewal interval from X^* to X. All subsequent renewals are scheduled earlier than if the increase had not taken place. Discounting and comparing the two alternative cost streams gives the marginal cost associated with the increase in traffic.

Figure 1. Renewal intervals with and without a marginal increase in traffic at $\tilde{x}$



There are some key features of this model that are addressed. First of all, the deterioration elasticity, i.e. the percentage change in quality (and subsequently rail age) from a percentage change in traffic needs to be estimated. Secondly, an estimate of the cost of a rail renewal is needed. Thirdly, we need to discount the cost based on the expected remaining life time of each track segment. The main results are given in table 3.

The estimated Weibull survival model shows increased renewal risks over time with respect to accumulated traffic volumes (positive duration dependence). The average change in rail life is estimated to around 0.1 percent from a 1 percent change in gross tonnage. Passenger gross tonnes generate a higher weighted marginal cost than freight, despite having a lower point estimate of the deterioration elasticity. This comes from a slightly different distribution of individual elasticities and average cost estimates. The model provides an opportunity to estimate marginal renewal costs, when a sufficient time-series of renewal cost data is unavailable.

Table 3. Main results from the survival analysis approach

Cost category	**Output variable**	**Deterioration elasticity***	**Marginal cost****
Track renewal	Passenger gross tonnes	-0.09	0.0025-30
Track renewal	Freight gross tonnes	-0.13	0.0019-20

* Mean deterioration elasticity

** Marginal cost expressed as weighted network means in Swedish Kronor per output kilometre

6.5 Paper V - Marginal Railway Infrastructure Costs in a Dynamic Context

In paper II and III, POLS and FE estimation is applied to our Swedish railway cost data. The final paper is an extension of the previously static models, by looking at potential dynamic effects.

We address three different hypotheses of dynamics that might affect our marginal cost estimates;

Hyp. 1, Future renewals affect current infrastructure operation and maintenance costs,

Hyp. 2, Historical traffic volumes affect current maintenance costs,

Hyp. 3, Historical maintenance costs affect current maintenance costs.

The first hypothesis is based on discussions with staff at Banverket that signalled difficulties in comparing track section costs over time if a major renewal is planned in the near future. Costs are cut prior a renewal as a part of a cost-minimising strategy. We estimate this model using a fixed effects estimator and dummy variables for large renewals in the near future.

The second hypothesis reflects inertia in reacting with maintenance activities to changes in traffic volumes. The fixed effects estimator is used once again, but we lose observations by introducing lagged variables.

The final hypothesis deals with the possibility of maintenance costs being affected by the level of maintenance undertaken in previous years. If we spend more money on maintenance one year, we can benefit from this in terms of reduced needs for maintenance in following years. This hypothesis is analysed using a dynamic GMM estimator.

Regarding our first hypothesis, we find evidence of forward-looking behaviour at Banverket. Both infrastructure operation and maintenance costs are reduced prior to a large renewal. Maintenance costs are reduced by approximately 12 percent on an annual basis when a renewal is planned within the coming two years.

For our second hypothesis, we find some evidence of traffic in previous years affecting the cost of maintenance in succeeding years. This is not surprising as there is a strong correlation between traffic volumes over time.

Finally, there is a strong negative relationship between the difference in maintenance costs in time periods *t*-1 and *t*. This indicates that spending on maintenance follows a cyclic pattern around some level to keep the track in steady-state. The main results from the alternative models are given in table 4.

Table 4. Main results from cost functions estimated by FE and GMM

Cost category	**Output variable**	**Cost elasticity***	**Marginal cost****
Infrastructure operation - Hyp. 1	Trains	-0.02	0.121
Maintenance - Hyp. 1	Gross tonnes	0.23	0.0063
Maintenance - Hyp. 2	Gross tonnes	0.63	0.0159
Maintenance - Hyp. 3 (Short-run)	Gross tonnes	0.31	0.0084
Maintenance - Hyp. 3 (Long-run)	Gross tonnes	0.20	0.0054

* Mean cost elasticity

** Marginal cost expressed as a weighted network mean in Swedish Kronor per output kilometre

We conclude that dynamic aspects are important and affect marginal cost estimates, but a more extensive data set is needed in order to address these issues properly, especially hypotheses 2 and 3.

7. Lessons Learned

In the previous section, the findings from the individual papers are summarised. In this closing section, some lessons learned and prospects for future research are highlighted.

To estimate marginal costs of railway infrastructure wear and tear, information about infrastructure management cost and output data from the railway sector is required. This can be either time-series, cross-sectional or a combination of both (panel). It has proven difficult to find long time-series of relevant data for this work, and the deregulation of the Swedish railway sector has not improved this situation. It is therefore most likely that cross-sectional or short panel data will have to be used in the same way as this study. The European railway policy requires only separate financial accounts between train operations and infrastructure, and several European countries have solved this by vertically separate these two parts into different organisations. This issue of cost separation is important, but not sufficient for marginal cost estimation. This thesis clearly shows that cost separation does not automatically generate the necessary data for detailed cost analyses. It is the joint quality of cost and traffic data combined with information on the infrastructure that determines the quality of marginal cost estimates. A data collection strategy that takes the need for marginal cost estimation into account is therefore essential for European railway organisations.

Given the data that anyway is available, it is necessary to choose an appropriate model and estimation method. We have seen that the choice of model and method has non-negligible consequences for the results. In table 5-7, the different elasticity and marginal cost estimates are summarised for infrastructure operation, maintenance and renewal respectively. A general observation is that estimates change for all cost categories when the method of pooled ordinary least squares is replaced with fixed effects. The focus in the thesis is not to provide a single answer to the question of the marginal cost of wear and tear. It is rather to show the impact on estimates from different model specifications and estimation techniques, and to try to understand the underlying significance of this. Failure to test for model specification can obviously give biased estimates, which can mislead policy makers.

Table 5. Infrastructure operation costs - main results

Method	Output variable	Cost elasticity*	Marginal cost**
POLS - Paper II	Trains	0.37	0.476
FE - Paper III	Trains	-0.01	0.127
FE - Paper V	Trains	-0.02	0.121

* Mean cost elasticity

** Marginal cost expressed as a weighted network mean in Swedish Kronor per output kilometre

Table 6. Maintenance costs - main results

Method	Output variable	Cost elasticity*	Marginal cost**
POLS - Paper II	Gross tonnes	0.21	0.0031
FE - Paper III	Gross tonnes	0.27	0.0073
FE - Paper V-a	Gross tonnes	0.23	0.0063
FE - Paper V-b	Gross tonnes	0.63	0.0159
GMM - Paper V-c (SR)	Gross tonnes	0.31	0.0084
GMM - Paper V-c (LR)	Gross tonnes	0.20	0.0054

* Mean cost elasticity

** Marginal cost expressed as a weighted network mean in Swedish Kronor per output kilometre

Table 7. Renewal costs - main results

Method	Output variable	Elasticity*	Marginal cost**
POLS - Paper II***	Gross tonnes	0.26	0.0055
FE - Paper III***	Gross tonnes	0.13	-
SA - Paper IV	Passenger gross tonnes	-0.09	0.0025-30
SA - Paper IV	Freight gross tonnes	-0.13	0.0019-20

* Mean elasticity. POLS and FE estimates are cost elasticities. SA estimates are deterioration elasticities

** Marginal cost expressed as a weighted network mean in Swedish Kronor per output kilometre

*** Aggregate of maintenance and renewal costs

Summarising the overall estimates, which are based on the variety of models, there are some common features to be pointed out. It is important to model infrastructure operation costs separate from maintenance and renewal as the character of this category is different. All elasticity estimates are below unity and in the majority of cases even below 0.5, i.e. there are economies of density. This result is irrespective of cost category. Maintenance costs show the least variation between the different econometric methods.

The current wear and tear charge in Sweden is SEK 0.0029 per gross tonne kilometre (Banverket, 2006) and our marginal cost estimates indicate that there is potential for increasing and diversifying this charge. In 2005, the track charge revenue was SEK 285 million. Plausible track charges from the selection of models in table 5-7 are SEK 0.1 per train kilometre for infrastructure operation, SEK 0.006 and 0.002 per gross tonne kilometre for maintenance and renewals respectively. Given the traffic volumes in 2005, the new charges would give around SEK 530 million in revenue to be paid by train operating companies, reducing the burden on Swedish tax-payers by almost SEK 250 million[3]. Still, a financial deficit in infrastructure management accounts from a marginal cost based pricing policy seems inevitable. To further improve the financial situation, instruments to charge for inter alia external costs related to noise (Andersson and Ögren, In press) or congestion and scarcity (Nash et al., 2004) are needed.

So what are the options for the future? There is an underlying assumption of cost minimisation behind the estimated cost functions. Preston (2002) compares the cost structure of Sweden and Britain, but concludes that it is difficult to define the optimal level. Kennedy and Smith (2004) apply a yardstick competition method for Britain's Network Rail to check for internal consistency and efficiency. They find substantial variation between network zones, and potential efficiency improvements of as high as 24 %, which questions the cost minimisation assumption. A similar analysis is possible to do with the data used in this thesis and is a potential for future work.

Differentiated charges are often on the policy agenda. So far, we have focused on deriving average estimates of marginal costs to be used on all traffic as a flat rate across the entire network. Only in paper IV, have we been able to derive separate estimates for freight and passenger trains, but still as a network average. From an efficiency point of view, one can

[3] We assume no changes in demand from the increased charges.

argue against the approach using flat rates as it means that only a fraction (if anyone) will pay the right price for its use of the railway infrastructure. The issue of differentiation is vast and covers individual charges for individual track sections in time and space as well as separating between vehicle types. However, moving into differentiated charges introduces a demand for higher quality data or pooling economic and engineering knowledge. There is a vast literature on multi-product cost functions (Caves, Christensen and Tretheway, 1980) and this would be an interesting field to explore in the future.

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