# Estimates of marginal infrastructure costs for different modes of transport

by

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Abstract:

One component of optimal prices for infrastructure use is the marginal cost of maintaining and operating infrastructure. While extensive studies on optimal congestion and environmental charges as well as the respective cost estimates are available much less attention has been paid to the estimation of marginal infrastructure costs. This paper presents results from a set of studies on marginal infrastructure costs for different modes of transport. It is based on research previously undertaken for the European Commission within the UNITE project (Unification of Marginal Costs and Accounts for Transport Efficiency in Europe). The studies employed different methodologies for estimating marginal costs ranging from econometric approaches up to engineering based methods. The focus of the analysis is on road and rail, however, the paper includes also results for an airport and for seaports.

# 1 Introduction

Optimal, e. g. social marginal cost based charging for infrastructure use requires quantitative evidence on the different cost components such as the marginal costs of infrastructure maintenance, repair, renewal and operation and the marginal cost of environmental damages, accidents and congestion. While extensive studies on optimal congestion and environmental charges are available much less attention has been paid to the estimation of marginal infrastructure costs, probably due to the assumed lower quantitative importance for pricing compared to environmental and congestion costs.

The existing literature on cost functions was either motivated by deregulation issues or aimed at measuring productive efficiency across firms over time (Caves et al. 1984, Bauer 1990, Grabkowski and Mehdian 1990, Talvitie and Sikow 1992). These studies focus on transport companies (trucking and rail companies, airlines) but do not deal explicitly with transport infrastructure. Infrastructure cost studies were only performed as full cost studies in Germany, Austria, Switzerland and France motivated by a public interest in cost information. Other full cost studies attempted to distinguish between fixed and variable costs and to allocate top-down percentages of variable costs to different vehicle categories based on empirical, engineering and expert judgement (see Link et al. 1999). Finally, engineering methods such as the AASHO Road Test (Highway Research Board 1961) provide a possible approach to the problem. For example, the so-called fourth power rule for the relationship between road damage and axle weight, derived within an engineering experiment, can be transformed into a cost function if renewal costs are assumed to be proportional to road damages.

The research summarised in this paper was aimed at closing the obvious gap in research. It presents the findings of a series of case studies analysing both link-based infrastructures such as road and rail links and terminal infrastructure such as airports and ports.[1] The findings discussed in this paper draw mainly from four road infrastructure studies covering Germany, Switzerland, Austria and Sweden, two studies on rail infrastructure covering Sweden, Finland and the UK, a Swedish seaport study and an airport case study for Finland. This paper is organised as follows: Chapter 2 describes the methodological approaches and chapter 3 the results of the case studies. Chapter 4 concludes.

[1] These case studies were performed within the EU funded research project UNITE (see Link et al. 2002).

# 2 Methodology and input data

The research was aimed at estimating short-run marginal costs, e. g. capacity was considered to be given and only those costs were analysed which can be assumed to vary with traffic volume in the short-run. These costs included maintenance, operation and renewals for link-type infrastructure (roads, rail tracks and inland waterways). For terminal infrastructure(seaports, airports) it was assumed that these types of costs are mainly driven by other factors while staff costs might be influenced by traffic volume. Consequently, for terminal infrastructure it was analysed whether and to what extent staff costs vary with traffic volume. A general methodological exception is the Swedish seaport study where in addition long run marginal cost behaviour was analysed.

## 2.1 Road

Econometric studies were performed for Germany, Switzerland and Austria while for Sweden an engineering-based approach was chosen. The decision on the type of approach was driven by the availability and quality of input data. Note, that both methods have advantages and caveats. While econometric approaches are based on observed behaviour of costs with the problem that the observed costs do not always follow technical needs resulting from the use of infrastructure, i.e. do not necessarily reflect true marginal costs, engineering-based methods are built on measured technical relationships which are not necessarily reflected in actual spending. They give rather an estimate of marginal costs under the assumption that all infrastructure assets are properly maintained and renewed.

To start with the econometric studies the type of data and the number of cases varied considerably between the three countries studied. For Switzerland and Austria it was possible to analyse different types of costs such as maintenance, upgrading and renewals while for Germany only data on renewal costs were available. The number of observations ranged from N=38 for Austria to N=424 and N=224 for Switzerland and Germany. The Swiss and Austrian data contained traffic data per vehicle types which, caused serious multicollinearity problems while ata on further explanatory variables was missing. Therefore, for both countries log-linear, single equation regressions were performed, with each equation including one of the traffic variables

$$\ln C_i = c + \beta \ln u_i \qquad (1)$$

where u denotes the traffic variable, tested for several vehicle categories and types of data such as mileages, gross-tonne kilometres and axle-load km, C is the cost variable, tested for different types of costs (operational maintenance cost, constructional maintenance cost, upgrade costs, renewal costs), and i indicates the motorway section or region. For the Swiss road network the log-linear model (1) was estimated both for pooled longitudinal and cross-sectional data. For Austria a cross-sectional analysis with the aggregated maintenance and renewal expenditures over 10 years was performed.

For Germany it was possible to test a translog cost function. However, both the field of application and the type of input data implied methodological deviations from the traditional translog approach. The research presented here sought to identify a functional relationship between renewal cost behaviour, traffic volume (which corresponds with the output vector **Y** in the traditional cost function) and different impact factors such as age of motorways, climate, maintenance history etc., rather than input factors such as capital, labour, material and energy. The cost information was obtained by evaluating physical renewal measures with unit costs. This different context implies that there is neither a sensible formulation of input cost shares nor a sensible restriction. Furthermore, the model does not include a price vector as explanatory variable. The type of input data did not allow to model possible changes of technologies for renewal measures. The traffic variables were expressed as the ratio $r_i$ of the average annual daily traffic volume (AADT) of trucks and passenger cars since a translog model with separate traffic variables for trucks" and passenger cars caused serious problems of multicollinearity (with the variance inflation factor between 15 and 56)[2]. The model estimated had the following form

$$\ln C_i = c + \sum_{j=1}^{m} \alpha_j D_{ij} + \sum_{k=1}^{K} \delta_k M_{ik} + \alpha_9 E_i + \alpha_{10} l_i + \beta_1 \ln r_i + \beta_2 \ln a_i + \frac{1}{2}\left(\beta_3 \ln^2 r_i + \beta_4 \ln^2 a_i + \beta_5 \ln r_i \ln a_i\right) \qquad (2)$$

$$r_i = \frac{u_{1i}}{u_{2i}} \, . \qquad (3)$$

[2] Translog-models estimated for one of the two traffic variables only achieved extremely poor R-squares.

where i indicates the motorway sections, c is a constant, C denotes the aggregated renewal costs per km from 1980 to 199 (at 2000 prices), $u_{1i}$ and $u_{2i}$ represent the AADT of trucks and passenger cars respectively. $E_i$ is a categorical (four level) variable indicating the level of renewal costs before 1980, $l_i$ and $a_i$ indicate the number of lanes and the age of each motorway section. $D_{ij}$ is a dummy variable for the federal state (j=1...10) and $M_{ik}$ is a categorical variable for the material used for upper layer (k=1..8).

Starting point for the engineering based study for Sweden was the assumption that the length of an interval between two pavement renewals depends on the traffic load which went over a certain road section measured as standard axles. Existing literature (Newbery 1988b, Small et al. 1989) assumes that the number of standard axles that can pass on a road before the pavement has to be renewed is a design parameter of road construction and thus independent of the traffic volume. In contrast to this assumption, the analysis presented here used new empirical knowledge which indicates that the number of standard axles which the road can accommodate is a function of the traffic volume (Wågberg 2001). It is assumed that the pavement will be renewed when road condition has a too poor standard, signalised in a cracking index which consists of three elements, namely the crackled surface, the longitudinal cracking and the transverse cracking. For estimating these three elements of the cracking index, data from the Long-term Pavement Performance Project in Sweden was used. The finally estimated lifetime of a pavement (T) is a function of the constant annual numbers of standard axles that pass the road and the strength of the road:

$$T = \left[\frac{\Theta(Q)}{Q}\right] e^{-mT} \qquad (4)$$

where $\Theta$ denote the number of 'standard axles' the pavement can accommodate, Q is the annual traffic volume measured as 'standard axles' and m indicates the climate dependent deterioration. For simplification the climate influence was neglected. The change of lifetime due to higher traffic loads was expressed by a so-called deterioration elasticity

$$\varepsilon = \frac{dT}{dQ}\frac{Q}{T} \quad . \qquad (5)$$

The marginal cost caused by shortening the renewal intervals due to higher traffic loads was obtained by differentiating the annualised present value of the road with the annual traffic volume. By using the deterioration elasticity $\varepsilon$ and an expression for the average costs AC, the marginal costs for a new road $MC_{New}$, an old road $MC_{Old}$ and an average road $MC_{Average}$ can be expressed as

$$MC_{New} = MC_{Old} = -(rT)^2 \frac{e^{rT}}{(e^{rT}-1)^2} \frac{C}{TQ} \varepsilon = -\alpha \varepsilon AC \tag{6}$$

$$MC_{Average} = -\varepsilon AC \tag{7}$$

$$AC = \frac{C}{\theta} = \frac{C}{QT} \tag{8}$$

$$\alpha = (rT)^2 \frac{e^{rT}}{(e^{rT}-1)^2} \tag{9}$$

where r is the interest rate and C stands for total costs. Note, that the marginal costs for an average road were derived by assuming that the age of roads is evenly distributed over the whole network.

If a real interest rate of 3 or 4 % is applied the parameter $\alpha$ takes a value between – 0.95 and – 1.00 and the marginal cost is in this case approximately the same for an average road as for a new or old road. The decisive parameter for the relationship between the average cost (AC) and the marginal cost (MC) is the value of the deterioration elasticity. The so-called fundamental theorem (Newbery 1988) says that average cost is equal to marginal costs. However, the formal expression of marginal costs as derived in (6) and (7) illustrates that this is only valid if there is no weather effect and if the number of standard axles the surface can withstand is constant, e.g. if the elasticity $\varepsilon$ becomes negative unity. The empirical analysis performed in the case study provides evidence that $\varepsilon$ is not equal to negative unity (see chapter 3). For interpreting the results one has to consider the basic assumptions of this analysis which where (i) Climate conditions have no influence on the renewal interval. (ii) The age of roads is equally distributed within the whole road network. (iii) Pavement is renewed if the cracking index has reached a defined terminal value.[3]

## 2.2 Rail

Although rail has formed a traditional field of cost function analysis, disaggregated data for rail track costs volume are rare. Sweden and Finland were the only countries with a sufficient data base for an econometric analysis. In this paper we will present this analyses and complement this research by a summary of research which was undertaken by the Rail Regulator in Britain in the period from 1997 to 2000 (ORR, 2000a).

The econometric analysis for Sweden and Finland applied the translog cost function proposed by Christensen et al. (1973). It was based on cross-sectional data for three years. The Swedish data contained information on gross ton kilometres, track maintenance costs $C_{ijt}$, track length , technical characteristics (number of switches, bridges and tunnels). The finally analysed data set included 169 observations for 1994, 176 observations for 1995 and 175 observations for 1996. The data excluded reinvestments and the maintenance costs referred to track-specific costs only, e.g. excluded common costs. The Finnish data set comprised information for the period from 1997 to 1999 with 93 observations for both 1997 and 1998 and 92 observations for 1999. In contrast to the Swedish data set, common costs were included and allocated to the track sections. Furthermore, information about spending on reinvestments such as track renewals were included. The average speed allowed on a track unit was used as a proxy for quality, and a dummy variable on electrification was used instead of the dummy variable on main and secondary lines in the Swedish data set. The finally specified models for the Swedish and the Finnish data included the track length $Y_{ijt}$, the utilisation level $u_{ijt}$ measured as gross tonnes, a vector of technical variables (number of switches, number of tunnels etc.) $z_{ijt}$, and for the Swedish analysis a vector of dummy variables $D_{ij}$ indicating the influence of districts as well as a dummy variable for main and secondary lines $I_i$:

$$\begin{aligned}\ln C_{ijt} &= c + \sum_{j=1}^{m} \alpha_j D_{ij} + \beta_{yt} \ln Y_{ijt} + \beta_{ut} \ln u_{ijt} + \\ &\frac{1}{2}\left(\beta_{yyt} \ln^2 Y_{ijt} + \beta_{uut} \ln^2 u_{ijt} + \beta_{yut} \ln Y_{ijt} \ln u_{ijt}\right) + \beta_I I_{ijt} + \beta_z' z_{ijt}\end{aligned} \qquad (10)$$

Note, that this model specification excludes the vectors of marginal prices for the input factors.[4] As the German motorway renewal cost study, this is not a classical translog cost function which links production factors and their prices to costs and output levels.

[3] This terminal value was set to S > 5 in the case study.

[4] Since both Sweden and Finland are fairly small countries with factor prices that are harmonised at large marginal prices are assumed to be equal a cross track units.

The analysis for the British rail network was based on three main sources: (i) on the marginal cost calculations performed by Railtrack itself, (ii) on a study performed by Booz Allen & Hamilton for the Office of the Rail Regulator, and (iii) on the decision taken by the Rail Regulator on the track charges. Britain's railway infrastructure manager, Railtrack, applies an engineering model to estimate track usage costs. Within this model the effect of an additional train on either the maintenance needs of the track or on the life of the track asset is calculated. Unit costs are applied to express these physical effects in monetary terms. The main input data used for the model are traffic data (train services, speeds, load of each service), number of axles and infrastructure data (track type, sleeper type, line speed by network segment). In contrast to the engineering based model the Rail Regulator put forward a top-down approach based on a review of international research on use dependent track costs (see Booz, Allan & Hamilton 1999). The results rely on a traditional accounting distinction between fixed and variable costs, but the categorisation is based on an extensive review of empirical evidence ranging from engineering studies to statistical analysis of past expenditures. Very high density railways as well as low density railways were studied, and the results were on the one hand obtained from predominantly freight railways (USA), while others were derived from predominantly passenger railways (Europe). A third source of insight into the level of marginal costs of rail infrastructure was obtained by analysing the Railtrack access charges finally derived by the Rail Regulator. As indicated above, the Regulator used a top-down-approach of splitting Railtracks total maintenance and renewal costs into fixed and variable costs, and applied the results of the Railtrack model to apportion the variable costs between vehicle types.

## 2.3 Airports

The research covered the airport of Helsinki where sufficient data for an econometric analysis was available. The analysis referred exclusively to infrastructure services. While transport operator services, commercial services and public sector services and cargo services related to non-aeronautical activities were excluded, services for freight flights on the aeronautical side were included. Two types of data were available: (i)Total costs (excluding depreciation, but including central administration staff) per service category in 2000, occurred both directly at Helsinki Vantaa airport and by subcontractors (outsourced services); (ii) Hourly data on scheduled staff, number of aircraft movements and passengers, collected for one winter and one summer week, both during the year 2000.

In contrast to the bulk of existing studies on airline's costs the data did not allow to perform a traditional cost function analysis which links total cost of production to production output, production factors and input prices. The analysis for Helsinki airport focused rather on labour costs as the dominant cost component for this airport and sought to identify the relationship between labour costs, aircraft movements and number of passengers in an hourly pattern. A series of linear models was applied with dummy variables for seasonal and calendar effects. The fact that for each service and even within the same service different kinds of agreements on extra salaries for evening and night work do exist was considered by introducing a categorical variable. Ongoing research which will be presented in the seminar uses multivariate time series analysis in order to solve autocorrelation problems occurred in the first model series.

### 2.4 Waterborne transport

In contrast to the research described in this paper so far, the analysis for Swedish seaports[5] followed both a short-run and a long run marginal cost approach.To start with the short run cost function analysis, it can be assumed that the wear and tear from using seaport infrastructure is almost negligible (similarly as it was for airports). Therefore the short run marginal cost analysis for port infrastructure focused on the direct cargo handling or stevedoring costs. To provide empirical evidence on the relationship between stevedoring costs and traffic volume a time series based regression analysis, both with a linear and an exponential form, was performed. The data referred to the port of Uddevala for which monthly data for the period from January 1973 to June 1976 was available. It was not possible to obtain more updated information. The data included amongst other, the total through-put of the port for twenty groups of commodities and the stevedoring costs expressed in total nominal wages paid every month.

The implicit idea behind the long-run cost analysis was that pricing policy should prevent over-expansion of capacity which might follow from not taking into account

[5] So far, not much quantitative research on the infrastructure costs of inland waterways is available. The UNITE project contained also a study on the infrastructure costs of the Rhine, however, it was largely based on expert opinions and due to the lack of sufficient statistical data no empirical analysis was possible.

(i.e. excluding from the price) the costs of capacity development. The methodological idea was that by means of time series analysis the full effect on the costs of capacity expansion caused by growing demand could be estimated. However, it has to be borne in mind that (i) investments in new capacity also imply user cost effects, and (ii) technological change and growing experience of the technology adopted during the long period of observation have to be considered. While the first aspect refers rather to the definition of the price relevant cost categories, the second aspect indicates a methodological problem of empirical estimation. The functional form used for estimating the relationship between the development costs TC, the throughput Q, the technological progress overtime and the learning by doing effect was

$$\log TC = \log a + b \cdot \log Q + c \cdot \log Q_{cum} + d \cdot year \qquad (11)$$

where $Q_{cum}$ indicates the cumulated port throughput. This term was chosen in order to reflect the effect of learning from experience (see for example Griffiths and Wall 2000, Pindyck and Rubinfeld 2001). By separately including the time in the function the approach tried to control for technical progress over time.

# 3. Results

## 3.1 Road

The research for road has produced rather diverging results for the four countries studied. We start with presenting first the econometric results (see table 1 for the parameter estimates). While the model fit of the log-linear models was moderate (with $R^2$ ranging from 26% to 65%), the fit for the translog model was with $R^2$=0.25 rather low. At least for Switzerland and Germany all statistical properties (absence of autocorrelation in the residuals, normality of residuals, homoscedasticity, no multicollinearity) required for OLS-estimation were fulfilled. Most of the parameters are significant at 5 % or at least at 10 % critical level. The Austrian results should not be overinterpreted since the sample was with 38 observation rather small.

Deriving marginal costs for different vehicle categories caused for all three econometric studies problems. The log-linear model for two vehicle types estimated for Austria was statistically insignificant and faced serious problems of multicollinearity. The use of the ratio between the AADT of trucks and passenger cars in the translog model for the German motorway network solved these multicollinearity problems but allowed to derive marginal costs only with respect to this ratio. With the single-equation log-linear models for Switzerland it is not possible to estimate marginal costs for different vehicle categories , either. .For Germany the marginal cost were obtained by fixing the AADT of passenger cars at the sample average AADT of passenger cars. For Switzerland, the marginal costs for different vehicle categories were approximated by (i) using estimates for gross-tonne km to calculate proxies for marginal costs of different vehicle categories, and (ii) applying cost shares of different vehicle categories obtained from an engineering approach to the overall marginal cost levels derived with equation (1).

**Table 1: Modelling results for Austrian, Swiss and German motorways**

| Model | N | $R^2$ | Coefficients | Std-error | T-value | Significance |
|---|---|---|---|---|---|---|
| **1. Austria** | 38 | 0.70 | | | | |
| constant | | | -7.233 | 2.374 | -3.046 | 0.004 |
| ln u | | | 1.046 | 0.111 | 9.433 | 0.000 |
| **2. Switzerland** | | | | | | |
| Model I (time series based) [2)] | 322 | 0.65 | | | | |
| constant | | | 1.315 | 0.565 | 2.329 | 0.20 |
| ln u | | | 0.686 | 0.028 | 24.385 | 0.00 |
| Model II (time series based): [3)] | 316 | 0.34 | | | | |
| constant | | | 1.065 | 1.117 | 0.954 | 0.341 |
| ln u | | | 0.715 | 0.056 | 12.718 | 0.000 |
| Model III (time series based): [4)] | 98 | 0.26 | | | | |
| constant | | | -3.620 | 3.007 | -1.204 | 0.232 |
| ln ug | | | 0.822 | 0.142 | 5.790 | 0.000 |
| Model IV (cross-sectional): | | 0.57 | | | | |
| constant | | | -8.558 | 1.504 | -5.690 | 0.000 |
| ln u | | | 0.550 | 0.077 | 7.191 | 0.000 |
| Dummy | | | -2.169 | 0.230 | -9.430 | 0.000 |
| Model V (cross-sectional) [6)] | | 0.58 | | | | |
| constant | | | -7.631 | 1.328 | -5.746 | 0.000 |
| ln u | | | 0.562 | 0.075 | 7.448 | 0.000 |
| Dummy | | | -2.040 | 0.228 | -8.930 | 0.000 |
| **3. Germany (translog model)[7)]** | 224 | 0.25 | | | | |
| constant | | | -0.427 | 0.230 | -1.857 | 0.065 |
| $\alpha_9$ | | | 0.749 | 0.222 | 3.368 | 0.001 |
| $\alpha_{10}$ | | | -0.917 | 1.387 | -0.661 | 0.509 |
| $\beta_1$ | | | 1.345 | 0.308 | 4.371 | 0.000 |
| $\beta_2$ | | | 0.457 | 0.252 | 1.815 | 0.071 |
| $\beta_3$ | | | 1.649 | 0.772 | 2.135 | 0.034 |
| $\beta_4$ | | | 0.437 | 0.907 | 0.482 | 0.630 |
| $\beta_5$ | | | -1.358 | 1.104 | -1.230 | 0.220 |
| $\beta_6$ | | | -1.789 | 1.110 | -1.612 | 0.108 |

[1)] Costs of maintenance and renewals. -[2)] Variables “operational maintenance costs” and “mileage of all vehicles”. – [3)] Variables “constructional maintenance costs” and “mileage of all vehicles”. - [4)] Variables “costs of upgrades and renewals” and “gross-tonne km”. - [5)] Variables “operational maintenance costs” and “total gross-tonne km”. – [6)] Variables “operational maintenance costs” and “total axle load equivalent-km”. [7)] The model contained also a vector of district dummies and a categorical variable indicating the type of material used for the upper layer. These variables are not reported here.

*Sources:* Herry and Sedlacek 2002, Schreyer et al. 2002, Link 2002.

The decisive parameter estimated with the engineering-based approach for the Swedish road network is the deterioration elasticity which was used for calculating marginal costs (see expressions 6 and 7). The main results was that this elasticity varies from – 0.1 on high quality roads with low traffic load up to – 0.8 on low quality roads with high traffic load (see Lindberg 2002). For a given traffic load the (negative elasticity increases with reduced strength of the road and for a given strength the (negative) elasticity increases with increased traffic.

**Table 2: Marginal cost estimates for road infrastructure costs**

| Country | Unit | Mean | Trucks | Passenger cars |
|---|---|---|---|---|
| Germany[1)] | € Cents/vkm | - | 0.05 ... 2.70[a)] | - |
| Austria[2)] | € Cents/vkm | 0.16 | 2.17[b)] | 0.07[b)] |
| Switzerland[1)] | € Cents/vkm | 0.67 ... 1.15 | 3.62 ... 5.17 | 0.42 ... 0.50 |
| Sweden[4)] | € Cents/vkm | - | 0.77 ... 1.86 | - |

[1)] Marginal renewal costs. –[2)] Marginal costs of maintenance and renewals. –[3)] Marginal costs of maintenance (operational and constructional) and upgrades & renewals. –. [a)] Marginal costs obtained from a model with the ratio between trucks and passenger cars where the AADT of passenger cars was fixed at the minimum and maximum observed value in the sample. –[b)] Based on log-linear regression model with vehicles-km of 2 vehicles classes. The model was statistically insignificant.

*Sources:* Link 2002, Schreyer et al. 2002; Herry and Sedlacek 2002, Lindberg 2002.

The engineering model work and the available input data allowed to present two types of results on marginal costs. In a first type of calculation an average pavement cost and the deterioration elasticity were used to calculate marginal costs per standard axle on roads with different roads strengt. The marginal costs lie in a range of 0.07 € per 100 standard axle kilometres up to 1.62 € per 100 standard axle kilometres (see figure 1). In a second type of calculation the available information for a sub-sample of 249 road sections was used. For these sections an average lifetime of 11.8 years and an elasticity of – 0.43 was estimated. The marginal costs per 100 standard axle kilometres were estimated to be 0.8 €, assuming an average overlay cost of 2.2 € per 100 standard axle kilometres. The estimated costs per standard axle were expressed as costs per vehicle-km (see table 3) by using data from the Swedish Road Administration on standard axles per vehicle type for four groups of vehicles. According to this calculation a marginal cost of 0.32 € per 100 vehicle kilometres for light duty vehicles (LDV) and of 1.86 € per 100 vehicle kilometres for the heaviest vehicles (HGV with trailer) was derived.

**Table 3: Average and marginal cost for the Swedish road subsample**

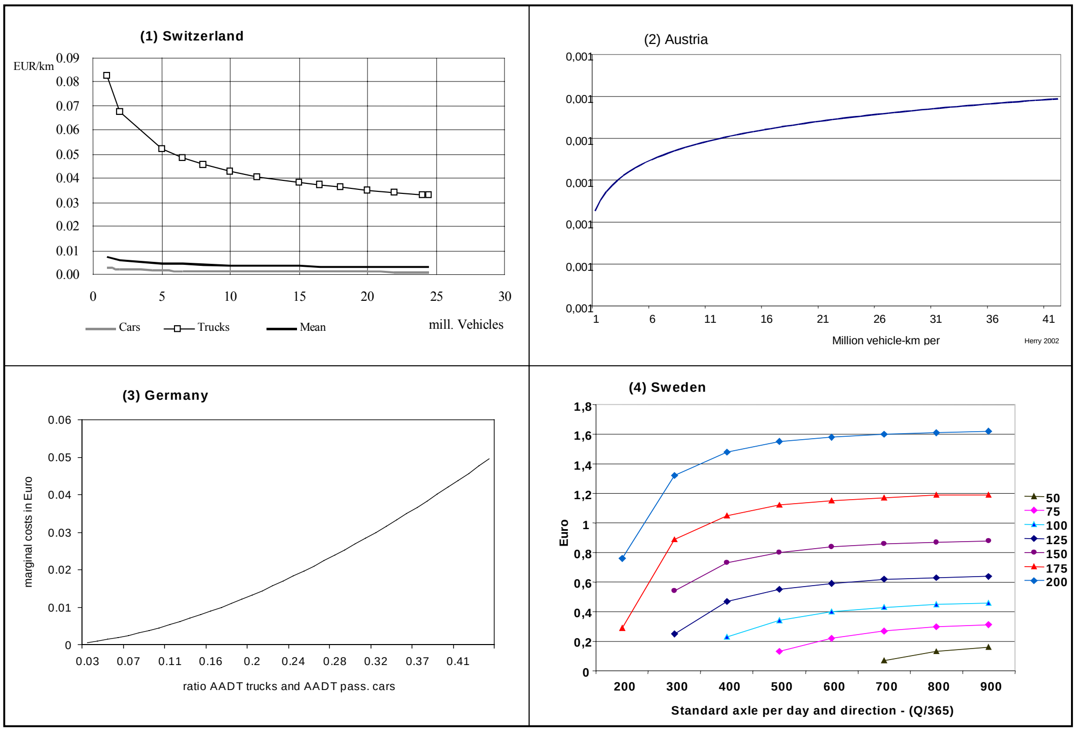
| | Mean | Std.Dev. | Minimum | Maximum | Number of cases |
|---|---|---|---|---|---|
| SCI [1)] | 133.997 | 44.3632 | 55.5224 | 269.104 | 249 |
| Vehicles (AADT) [2)] | 5131.57 | 2278 | 1290 | 10900 | 249 |
| WIDTH (m) | 11.7209 | 3.75126 | 7.5 | 20 | 249 |
| Q (per day and direction) [3)] | 578.94 | 379.485 | 137 | 1320 | 249 |
| OVERLAY COST (kSEK/km) | 37.0 | 8.7 | 30.5 | 66.0 | 249 |
| LIFETIME (year) | 11.8103 | 3.11661 | 3.36859 | 16.9688 | 249 |
| Deterioration elasticity | -0.431342 | 0.221295 | -0.80211 | -0.00908 | 249 |
| Average costs (SEK/Sakm) | 0.022 | 0.016 | 0.006 | 0.093 | 249 |
| Marginal costs (SEK/Sakm) | 0.008 | 0.0061 | 0.0002 | 0.038 | 249 |

[1)] Road Surface Curvature Index. – [2)] AADT = Annual average daily traffic. – [3)] Number of standard axles.
*Source:* Lindberg 2002.

As table 2 indicates, the variance even within the results obtained by econometric approaches is considerable. However, a direct comparison is hampered due to the fact that the cost and vehicle categories included in the modelling differ.With respect to the cost components included it is possible to compare Sweden and Germany (both analysed renewal costs) and Austria and Switzerland (covering maintenance and renewal costs), although methodological differences and differences of the road types have to be taken into account, too. The range between the minimum and maximum estimate for Germany is higher than for Sweden. A comparison between Switzerland and Austria shows considerable differences, too. However, this should not be overinterpreted since a rather small number of cases was available for Austria.

The models estimated lead to rather diverging shapes of the marginal road cost curves (figure 1). Both for Austria and for Sweden a degressively growing marginal cost function was derived, the marginal renewal costs for German motorways costs grows progressively with an increase of the ratio between trucks and passenger cars, and the analysis for Switzerland even produced a decreasing cost curve. The results (except those for Austria) indicate that the costs for maintenance and renewals seem to follow the neo-classical u-shaped cost curve, but are ambiguous with respect to the part of the „u“. The a priori expectation was that costs increase progressively with axle loads as it is suggested by the AASHO road test. The German results confirm this assumption while those for Austria and Switzerland would reject it. However, it should be borne in mind, that the cost curves for Austria and Switzerland are in the relevant range of traffic loads almost constant. The progressively increasing marginal cost curve for motorway renewals in Germany differs from the result for the Swedish road network. This might be explained by the fact that the Swedish analysis used the absolute amount of traffic load while for Germany the proportion between trucks and passenger cars was used.

**Figure 2: Marginal cost curves for road infrastructure costs in Austria, Switzerland, Germany and Sweden**




## 3.2 Rail

Both for Sweden and Finland, the translog specification of the functional relationship between costs and explanatory variables provided a good basis for understanding the spending pattern on track maintenance. R-squares of 77 % for the full Swedish model, of 74 % for the restricted Swedish model (excluding bridges, tunnels and district dummies), and of 83 % for the Finnish data proved high explanatory power of this approach (table 4). The model for Sweden contained significant parameters with the expected signs for the parameters of main interest, namely for track length and utilisation. Insignificant estimates were obtained for the second order term for track length, for two parameters for the number of bridges, for two parameters for the tunnel factor and for one parameter of the dummy variable for main and secondary lines. The model specification for Finnland yielded significant coefficients for track length, but the corresponding coefficient for traffic load was only significant at the 10 % level in a one-tail test. From this one could conclude that obviously the spending behaviour in Finland does not respond to variations in traffic load in the same way as in the Swedish data. For the Finnish data set an attempt was made to include reinvestments. However, since only observations from three specific years rather than a long period of time was available this attempt failed. Only two variables were significant with the electrification dummy and the squared utilisation capturing most of the effect on the cost.

**Table4: Parameter estimates for the translog approach applied to rail track maintenance costs in Sweden and Finland**

| **Sweden**[1] | Equation[2] | | Equation[3] | |
|---|---|---|---|---|
| | Est. | t-value | Est. | T-value |
| $\alpha$ | -6.749 | -3.924 | -6.828 | -4.210 |
| $\alpha_{95}$ | -0.005 | -0.093 | 0.000 | 0.003 |
| $\alpha_{96}$ | 0.013 | 0.241 | 0.005 | 0.292 |
| $I$ / $ß_I$ | 0.026 | 0.342 | 0.004 | 0.048 |
| $y$ / $ß_y^*$ | 2.338 | 5.943 | 2.023 | 5.589 |
| $u$ / $ß_u^*$ | 0.986 | 5.051 | 1.037 | 5.692 |
| $yu$/ $ß_{yu}^*$ | -0.104 | -5.868 | -0.096 | -5.665 |
| $y^2$ / $ß_{yy}$ | -0.010 | -0.294 | 0.023 | 0.786 |
| $u^2$ / $ß_{uu}$ | -0.014 | -2.288 | -0.017 | -2.995 |
| Bridge | 0.005 | 0.708 | | |
| $Bridge^2$ | 0.000 | -0.459 | | |
| Switches | 0.011 | 3.601 | 0.010 | 3.462 |
| $Switches^2$/100 | -0.006 | -1.184 | -0.005 | -1.169 |
| INDX | 0.210 | 2.290 | 0.269 | 3.022 |
| $INDX^2$ | -0.028 | -3.145 | -0.033 | -3.773 |
| $R^2$ | 0.767 | | 0.736 | |
| **Finland**[4] | Maintenance Cost | | With Reinvestments | |
| | Est. | t-value | Est. | t-value |
| $\alpha$ | 8.780 | 6.645 | 10.764 | 2.967 |
| $\alpha_{98}$ | -0.104 | -2.145 | -0.036 | -0.269 |
| $\alpha_{99}$ | -0.139 | -2.830 | -0.051 | -0.381 |
| $I$ / $ß_I$ | -0.318 | -4.936 | -0.550 | -3.102 |
| $y$ / $ß_y^*$ | 1.504 | 3.462 | 1.408 | 1.179 |
| $u$ / $ß_u^*$ | 0.167 | 1.501 | -0.326 | -1.065 |
| $yu$/ $ß_{yu}^*$ | 0.001 | 0.071 | -0.018 | -0.341 |
| $y^2$ / $ß_{yy}$ | -0.104 | -2.766 | -0.078 | -0.754 |
| $u^2$ / $ß_{uu}$ | -0.006 | -1.519 | 0.026 | 2.234 |
| Switches | 0.010 | 4.460 | 0.012 | 1.889 |
| $Switches^2$/100 | -0.003 | -2.264 | -0.001 | -0.379 |
| SPEED | 0.013 | 3.298 | 0.005 | 0.478 |
| $SPEED^2$/100 | -0.013 | -3.287 | 0.009 | 0.809 |
| $R^2$ | 0.827 | | 0.498 | |

[1] N = 520. -[2] Full model. Included also 19 district dummies and a categorical variable for tunnels (in seven levels) not reported here. -[3] Restricted model. -[4] N = 278.

*Source:* Johansson and Nilsson 2001.

The main result of the econometric analysis is that track maintenance seems to be a decreasing cost activity. The study confirmed the traditional "u" shape of cost functions, however, referring to the falling part of the "u". The interpretation of this is that higher traffic loads lead to lower marginal maintenance costs. Costs do not vary linearly with variation in traffic and track length, but the detected non-linearities are not very strong. Furthermore, maintenance activities in Sweden and Finland are not very responsive to variations in traffic load. The cost elasticity with respect to track utilisation calculated for the Swedish network falls when traffic load increases and remains constant after exceeding a certain threshold of gross ton kilometres. The mean of this elasticity is 0.17 indicating decreasing average maintenance costs. Although for Finland this elasticity was only estimated with a lower precision than for Sweden it is below unity and the magnitude is with 0.167 very similar. The marginal maintenance costs (table 5) range from 0.117 SEK to 0.147 FIM in 1995. They were calculated as "average marginal costs" both for the network as a whole and for the main and secondary lines separately[6]. All estimated marginal costs are for the Finnish data higher than for Sweden. The results indicate that with marginal cost pricing no more than 17 % of maintenance costs in Finland and no more than 12 % of those in Sweden would be recovered.

**Table 5: Estimates of marginal maintenance cost for the Swedish and Finnish rail network in € Cent per gross tonne-km (at 1995 and 2000 exchange rates)[1)]**

| | Sweden | | Finland | |
|---|---|---|---|---|
| | 1995 | 2000 | 1995 | 2000 |
| ALL | 0.013 | 0.014 | 0.017 | 0.027 |
| Main/electrified | 0.0088 | 0.0099 | 0.013 | 0.020 |
| Secondary/non-electrified | 0.097 | 0.11 | 0.029 | 0.045 |

[1)] 1 Euro (ECU) was SEK 9.332 in 1995 and SEK 8.446 in 2000.

*Source:* Johansson and Nilsson 2001.

For the British rail network, Railtrack's modelling results indicate that between 29 % and 32 % of the overall level of expenditure on maintenance and renewals of tracks may be regarded as variable. Booz Allen & Hamilton 1999 which derived variable costs per cost category from an extensive international review and applied them to the Railtrack cost figures by cost category, suggests with a range of 21 % to 23 % a somewhat lower

[6] For this purpose the track activity on each track section was weighted by dividing the gross tonne kilometres at each section by total gross tonne kilometres on the whole network.

level of cost variability than Railtrack. It should be borne in mind that this percentage has rather the character of a top-down recommendation and, moreover, it does not say anything on the functional form of marginal costs. It implicitly assumes that average variable costs can be used to approximate marginal costs. Given the problems to obtain sufficient data for econometric or engineering-based analyses, and considering the fact that the econometric studies for Sweden and Finland found only slight non-linearities, the top-down approach might be a fallback method.

**Table 6: Estimation results for Helsinki airport**

| Dep. variable: | $R^2$ | traffic variable | | Additional | | Weekends | | Season | | Constant | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| personnel in ... | % | coeff. | (t) | coeff. | (t) | coeff. | (t) | coeff. | (t) | coeff. | (t) |
| **model with number of aircraft movements** | | | | | | | | | | | |
| All services | 90,5 | 1,239 | (13,14) | -35,72 | (-28,7) | -4,25 | (-2,44) | -13,07 | (-8,76) | 116,4 | (36,7) |
| Traffic Control Services | 76,1 | 0,1566 | (5,10) | -7,31 | (-18,0) | -4,55 | (-8,04) | 0,71 | (1,47) | 17,5 | (16,8) |
| Maneuvering Area Services | 85,6 | 0,0388 | (2,03) | -2,01 | (-8,03) | 0,56 | (1,61) | -12,65 | (-42,1) | 26,8 | (41,9) |
| Apron Area Services | 81,2 | 0,0903 | (6,63) | -3,65 | (-20,3) | -2,03 | (-8,09) | -1,32 | (-6,16) | 12,6 | (27,3) |
| Passenger Services | 85,1 | 0,7773 | (10,47) | -22,24 | (-22,7) | 1,78 | (1,30) | 0,45 | (0,38) | 53,1 | (21,3) |
| Ground Transport Services | 44,0 | 0,1761 | (9,56) | -0,51 | (-2,12) | -0,06 | (-0,19) | -0,25 | (-0,87) | 6,6 | (10,6) |
| All services | 64,8 | 3,10 | (24,8) | | _ | | _ | | _ | 39,1 | (14,1) |
| **model with number of passengers** | | | | | | | | | | | |
| All services | 89,6 | 0,0144 | (11,4) | -39,80 | (-35,2) | -10,83 | (-6,29) | -14,55 | (-9,35) | 130,9 | (52,5) |
| Traffic Control Services | 74,1 | 0,0015 | (3,66) | -8,01 | (-22,3) | -5,40 | (-9,89) | -0,40 | (1,07) | 19,8 | (25,1) |
| Maneuvering Area Services | 85,4 | -0,00004 | (-0,16) | -2,39 | (-10,9) | 0,34 | (1,00) | -12,70 | (-42,1) | 28,0 | (57,9) |
| Apron Area Services | 80,5 | 0,0010 | (5,48) | -3,99 | (-25,0) | -2,51 | (-10,4) | -1,43 | (-6,55) | 13,7 | (39,1) |
| Passenger Services | 85,0 | 0,0098 | (10,3) | -24,40 | (-28,5) | -2,32 | (-1,78) | -0,48 | (-0,41) | 61,0 | (32,4) |
| Ground Transport Services | 42,6 | 0,0022 | (9,02) | -1,04 | (-4,88) | -0,99 | (-3,05) | 0,46 | (-1,58) | 8,5 | (18,0) |
| All services | 47,0 | 0,0401 | (17,2) | _ | | _ | | _ | | 54,8 | (17,9) |
| Source: JP Transplan Ltd. | | | | | | | | | | | |

### 3.3 Airports

With the linear regression models it was possible to explain 90% of the variations in the number of total personnel by the independent variables. Those models which considered each service separately were characterised by lower but good model fits (except for ground transport services). The significance of the independent variables differed between the type of services. When using the number of passengers instead of the number of aircraft movements as an independent variable similar results were obtained.

The weekend dummy has more significance when using the number of passengers which can be explained by the higher occupancy rates of aircrafts during weekends. Note, however, that all these results have to be seen against the background that problems with auto-correlated residuals occurred. Marginal costs can directly be taken from the β-coefficient of the linear models. An extra aircraft movement needs, on average, one person or more from the airport personnel. Expressed in monetary terms the marginal costs can be estimated to € 38 for an extra aircraft movement. This estimate corresponds well with earlier findings for US airports. Morrison and Winston 1989 report for maintenance, operation and administration of US airports marginal cost estimates of $ 22.09 per aircraft movement. If this figure is inflated to 2000 dollars[7] and adjusted to €, an estimate of € 32.97 per aircraft movement is obtained which comes close to the result for Helsinki airport.

## 3.4 Waterborne transport

Both types of regression analyses were faced with the problem of only few observations (42 observations for the analysis of stevedoring costs and 38 observation for the analysis of port development costs). Furthermore, the data base for the stevedoring cost analysis referred to figures from the 70's.

**Table7: Regression analysis for stevedoring costs on port throughput[1)] - port of Uddevala**

| Type of regression | Number of observations | Constant | Throughput coefficient | t-value | $\bar{R}^2$ |
|---|---|---|---|---|---|
| Exponential | 41[a)] | 0.101 | 1.23 | 8.47 | 0.60 |
| Exponential | 42 | 0.234 | 1.16 | 9.28 | 0.67 |
| Linear | 41[a)] | -13.369 | 1.658 | 9.66 | 0.69 |

[1)] Dependent variable = stevedoring costs; independent variable = port throughput. – [a)] Excludes one observation which ws an outlier.

*Source:* Jansson and Ericsson 2002.

The regression analysis for the stevedoring costs had an explanatory power between 60 % and 69 %, but is ambiguous regarding the functional form. While the result of the linear regression indicates that there is a strict proportionality between the stevedoring wage costs and the throughputs, the exponential regression indicates that elasticities between stevedoring costs and throughputs were greater than unity (1.23 if analysing 41

[7] The index of landing fees published by the Air Transport Association was used (www.airlines.org).

observations and 1.16 if analysing 42 observations). It seems impossible to draw any firm conclusion from these results.

The regression model for development costs was able to explain 86 % of the variance of total development costs. All coefficients are statistically significant and have the expected signs (table 8). A major methodological problem with this analysis was the high correlation (0.912) between time and the logarithm of cumulative throughput indicating problems of multicollinearity. Dropping one or the other of the two variables of the equation, however, does neither change the signs of the coefficients nor the significance, and the parameter estimates were only slightly affected. Both hypotheses on homoscedasticity and absence of autocorrelation in the residuals could not be rejected at the 10 percent critical value. Although the results refer to the 10 percent level only and despite the multicollinearity problem, the approach seems to be a good empirical estimation of the long run total cost-function. The results of the regression analysis were used to calculate the ratio of price-relevant long run marginal cost to the port service producer average cost, $MC/AC_{prod}$. The elasticity of total (producer and user) costs with respect to throughput was found to be 0.59. Furthermore, the ratio between average user costs and average producer costs was derived from the empirical material and was calculated to be 1.17 (average value for all 38 years) and to 1.39 respectively (average value for the last 10 years only). Applying these ratios and the cost elasticity to calculate the ratio between marginal costs and average producer costs $MC/AC_{prod}$ yields 0.11 and 0.02 respectively.

**Table 8: Regression analysis of the total costs on port throughput, cumulative port throughput and time at the port of Norrköping**

| Model[1)] | B | Std. Error | t-value | Sig. |
|---|---|---|---|---|
| Constant | 32.883 | 3.291 | 9.991 | 0.000 |
| LN_Q | 0.590 | 0.060 | 9.905 | 0.000 |
| LN_QCUM | -0.09234 | 0.021 | -4.390 | 0.000 |
| T | -0.01031 | 0.002 | -5.572 | 0.000 |

[1)] Dependent variable = total costs; independent variables = port throughput Q,cumulative throughput QCUM and time T.

*Source:* Jansson and Ericsson 2002.

# 4 Conclusions

The research presented in this paper provided evidence that for rail tracks and road infrastructure it is mainly the cost of maintenance, repair and renewal that vary with traffic volume while for terminal infrastructure such as ports and airports it is staff costs which varies in the short run with traffic. Furthermore, the estimation results were mostly consistent with the neoclassical u-shaped curve of marginal costs. However, in many cases the detected non-linearities were rather weak in the relevant range of traffic variables (for example the results for rail tracks in Sweden and Finland, but also the road results for Switzerland and Austria). Except for the road sector there was no a-priori assumption (neither from theory nor from practice) for the area of the traditional "u"-shaped marginal cost curve which applies to the context studied in the case studies. For the road sector the AASHO-Road test suggests a progressively increasing cost curve, i.e. refers to the increasing branch of the "u". From the case studies there is no general answer on this question. The analyses for the Swedish and Finnish rail network, the results for Swiss roads and the long run marginal cost approach for Swedish seaports identified a cost shape which follows the falling branch of the "u". The results for German motorway renewal costs and for the stevedoring cost analysis for seaports provided evidence for the increasing part of the "u". The Swedish and Austrian road case studies identified degressively growing marginal costs. These obvious differences of cost functions between modes can be caused either by methodological differences or by real differences of cost behaviour, or by a combination of both.

Finally, it should be borne in mind that the estimation of marginal infrastructure costs is a field with much less empirical evidence than in particular the estimation of marginal environmental or congestion costs. A broader research basis is necessary in order to enable a generalisation of results for policy decisions. Especially for those modes where evidence from only one application (for example airports, seaports) or from applications with too similar and not typical contexts (for example the rail case studies for two networks with low traffic density) is available, more research would be desirable. Studies which apply both the econometric and the engineering approach to the same data set would be of great interest for a methodological comparison.

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