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An econometric analysis of

motorway renewal costs in Germany

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Contents

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Zusammenfassung

Die in diesem Diskussionspapier vorgestellte Arbeit analysiert den Zusammenhang zwischen den Erneuerungskosten auf Autobahnen einerseits und der Verkehrsbelastung sowie den Faktorinputpreisen für Arbeit, Material und Kapital andererseits. Die Untersuchung basiert auf Querschnittsdaten für das westdeutsche Autobahnnetz für den Zeitraum von 1980 bis 1999. Unter Verwendung eines Translog-Ansatzes werden zwei Modelle für Kostenfunktionen der Straßenerneuerung geschätzt. Modell I beschreibt den ökonomischen Prozess der Straßenerneuerung als Zusammenhang zwischen den Erneuerungskosten, der erneuerten Fläche und den Faktorpreisen für Arbeit, Material und Kapital. Ein zweites Modell (Modell II) orientiert sich stärker am Prozess der Straßenschädigung und Kostenentstehung und bildet den Zusammenhang zwischen Erneuerungskosten, Verkehrsbelastung und wiederum den Faktorpreisen für Arbeit, Material und Kapital ab.

Die Schätzergebnisse für Modell I zeigen, dass im Prozess der Straßenerneuerung Material und Arbeit komplementäre Faktorinputs darstellen, während Kapital und Arbeit sowie Kapital und Material Substitute sind. Darüber hinaus ergeben sich aus den Modellergebnissen Economies of Scale bei der Straßenerneuerung, die darauf hindeuten, dass bei der Vergabe von Straßenerneuerungsarbeiten größere Lose sinnvoll erscheinen, vorausgesetzt, dass dem nicht Restriktionen hinsichtlich unerwünschter Verkehrseinschränkungen entgegenstehen.

Modell II ermöglicht die Ableitung von Grenzkosten der Infrastrukturbenutzung durch den Güterverkehr, die für die Bestimmung optimaler Preise nach dem Prinzip der sozialen Grenzkosten bedeutsam sind. Diese Information ist unmittelbar relevant für die Preispolitik im Verkehr. Die sich aus Modell II ergebende Kostenelastizität (das Verhältnis von Grenzkosten und Vollkosten) ist eine degressiv steigende Funktion der Verkehrsbelastung und liegt zwischen 0,05 und 1,17. Aus der Multiplikation mit den Durchschnittskosten ergeben sich hieraus Grenzkosten zwischen 0,08 bis 1,87 €pro Fahrzeugkilometer.

Abstract

This paper analyses the cost behaviour of motorway renewal costs with the aim to derive an estimate of marginal infrastructure costs per vehicle-km of trucks as part of optimal road user charges. The analysis is based on cross-sectional data of motorway renewal costs and traffic volume per motorway section in Germany during the period 1980-1999. The translog model estimated in this paper includes the factor input prices for labour, material and capital, the average annual daily traffic volume of trucks and passenger cars with the respective second-order terms, and a set of dummy variables for regions (the German länder) as well as for the type of material used for renewal as the most important explanatory variables. In contrast to this, we could not find any significant influence of the age of motorway sections, the past renewal expenditures and the climate conditions measured as days with temperature fluctuations around zero. The cost elasticity, i.e. the relationship between marginal and average costs found in this analysis ranges from 0.05 up to 1.17 with a digressive increase of marginal costs.

1. Background

One component of optimal prices for road use is the marginal cost of road maintenance and renewal. 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 road infrastructure costs. Econometric studies on cost functions for road infrastructure are rare[1]. *Newbery* 1988a, *Newbery* 1988b and *Newbery* 1989 provide theoretical attempts to the problem but lack the empirical evidence. Other studies such as *Talvitie/Sikow* 1992 analyse rather the productive efficiency of highway construction work by means of frontier cost functions. Cost allocation studies in Germany, Switzerland, Sweden and other countries conducted within the context of public road accounts usually assume a linear cost curve with marginal costs equal to variable costs and derive the fraction of variable costs based on expert opinions and judgements (see *Link et al.* 1999). Alternative approaches are engineering experiments such as the AASHO Road Test (see *Highway Research Board* 1961) which concluded the so-called fourth power rule reflecting the relationship between axle weight and road damages. However, the opportunities to conduct large-scale experiments are rather limited. *Small et al.* 1989 have introduced an engineering based approach of estimating an elasticity of road deterioration with respect to axle-loads. This approach was also applied in *Lindberg* 2002 who uses measurements of road conditions from the Swedish Long-Term Pavement Management Programme.

The analysis described in this paper employs a translog cost function approach to the problem. It analyses the renewal costs of German motorways during the period 1980-1999 based on cross-sectional data on motorway renewal expenditures, factor inputs and factor prices and traffic volume in West Germany. The paper is organised as follows: Chapter 2 discusses the methodological approach. Chapter 3 describes the input data used. Chapter 4 presents the estimation results and derives marginal renewal costs. Chapter 5 concludes.

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[1] This is also true for other modes than road. Exceptions are *Johansson/Nilsson* 2001 which estimated a translog cost function for rail maintenance costs in Sweden and Finland, and *Gaudry/Quinet* 2003 which derived a Box-Cox cost function for rail maintenance in France.

2. Methodology

Over the last 30 years economic literature has suggested a variety of different functional forms to describe producers behaviour. The translog approach, introduced for example in *Berndt/Christensen* 1973 and *Christensen et al.* 1975, has remained to be the most frequently used form (for an overview of applications in transport see *Oum/Waters* 1998). It imposes only few restrictions on the underlying production technology, allows a simple computation of substitution elasticities and contains all relevant properties of neoclassical production theory such as factor substitution, economies of scale and technological change. The Box-Cox model later on suggested by *Berndt/Khaled* 1979 is an even more general tool which contains the generalised *Leontief* function and the multiple-output translog function as special cases.

The major methodological difference between the context analysed in this paper and traditional cost functions employed so far in transportation research is the definition of the output variable. Defining the traffic volume of different vehicle types as output variable is not as straightforward as in existing cost function studies for example for the trucking industry or for rail transport (for example *Daughety et al.* 1985, *De Borger* 1992, *Cantos* 2000). While train-km, gross-tonne-km or passenger-km in rail transport are produced by the rail company with a combination of factor inputs such as energy, material, labour and capital, the factor inputs used for renewal work of motorways are not those used for producing vehicle-km of passenger cars and goods vehicles. The latter are produced by the factor inputs of haulage companies or individuals. The obvious way to define the output of motorway renewal work is a measurement of renewed road, expressed for example as sqm or cbm. This allows an analysis of factor input substitution, productivity and economies of scale. Since the main interest of this paper is to estimate marginal costs of infrastructure use, the logical consequence would be to incorporate traffic volume with the respective second-order and interaction terms into such a basic economic model. However, initial modelling attempts revealed that the strong effect of the output variable, measured as sqm renewed road, leads to insignificant and implausible parameter estimates for the traffic variables, in particular for goods vehicles. Therefore, two different translog models were adopted to analyse motorway renewal costs.

Model I seeks to analyse the economic process of renewing motorways as such, e.g. explaining the renewal costs C_i by the output variable Y_i defined as the sqm of motorways renewed at each section i over the analysis period, and a vector of input prices $W^{'} = \left(w_e, w_m, w_c \right)$ for

labour, material and capital. D_{ij} are dummy variables indicating the federal state j (j=1,…,m; m=8), and M_{ik} denote dummy variables for the material used for renewals (k = 1,..., K; K = 7, see table 1). This basic model has the form

$$
\begin{aligned}
\ln C_i = {} & c + \sum_{j=1}^{m} \alpha_j \cdot D_{ij} + \sum_{k=1}^{K} \delta_k \cdot M_{ik} + \beta_y \cdot \ln Y_i + \beta_l \cdot \ln W_{li} + \beta_m \cdot \ln W_{mi} + \beta_c \cdot \ln W_{ci} \\
& + \frac{1}{2} \cdot \left(\beta_{yy} \cdot \ln Y_i \cdot \ln Y_i + \beta_{ll} \cdot \ln W_{li} \cdot \ln W_{li} + \beta_{mm} \cdot \ln W_{mi} \cdot \ln W_{mi} + \beta_{cc} \cdot \ln W_{ci} \cdot \ln W_{ci} \right) \qquad (1) \\
& + \beta_{yl} \cdot \ln Y_i \cdot \ln W_{li} + \beta_{ym} \cdot \ln Y_i \cdot \ln W_{mi} + \beta_{yc} \cdot \ln Y_i \cdot \ln W_{ci} \\
& + \beta_{lm} \cdot \ln W_{li} \cdot \ln W_{mi} + \beta_{lc} \cdot \ln W_{li} \cdot \ln W_{ci} + \beta_{mc} \cdot \ln W_{mi} \cdot \ln W_{ci} .
\end{aligned}
$$

The cost-minimising factor demands are obtained by applying *Shephard*'s (1970) lemma

$$
S_l = \frac{\partial \ln C_i}{\partial \ln W_{li}} = \beta_l + \beta_{ll} \cdot \ln W_{li} + \beta_{yl} \cdot \ln Y_i + \beta_{lm} \cdot \ln W_{mi} + \beta_{lc} \cdot \ln W_{ci} \qquad (2)
$$

$$
S_c = \frac{\partial \ln C_i}{\partial \ln W_{ci}} = \beta_c + \beta_{cc} \cdot \ln W_{ci} + \beta_{yc} \cdot \ln Y_i + \beta_{lc} \cdot \ln W_{li} + \beta_{mc} \cdot \ln W_{mi} \qquad (3)
$$

$$
S_m = \frac{\partial \ln C_i}{\partial \ln W_{mi}} = \beta_m + \beta_{mm} \cdot \ln W_{mi} + \beta_{ym} \cdot \ln Y_i + \beta_{lm} \cdot \ln W_{li} + \beta_{mc} \cdot \ln W_{ci} \qquad (4)
$$

The necessary conditions for homogeneity in input prices and for symmetry are

$$
\sum_i \beta_i = 1, \quad \sum_i \sum_j \beta_{ij} = 0, \quad \sum_i \beta_{yi} = 0, \text{ and } \beta_{ij} = \beta_{ji} \quad \text{respectively, where } i = l, m, c.
$$

Due to the fact that the dependent variable was constructed as the sum of renewal expenditures over 20 years (see chapter 3), the model does not allow to analyse possible changes of technologies for renewal measures.

Model II establishes the relationship between renewal costs and the traffic volume u_{fi} and u_{pi} of goods vehicles and passenger cars respectively, expressed as the annual average daily traffic volume (AADT). E_i are the renewal costs before the period of analysis (defined as catego-

rical variable with the levels 0, 1, 2, 3), l_i is the number of lanes, a_i is the age of motorway sections. The cost behaviour is then described as

$$
\begin{aligned}
\ln C_i = {} & c + \sum_{j=1}^{m} \alpha_j \cdot D_{ij} + \sum_{k=1}^{K} \delta_k \cdot M_{ik} + \gamma_1 \cdot E_i + \gamma_2 \cdot \ln l_i \\
& + \beta_l \cdot \ln p_{li} + \beta_m \cdot \ln p_{mi} + \beta_c \cdot \ln p_{ci} + \beta_f \cdot \ln u_{fi} + \beta_p \cdot \ln u_{pi} + \beta_a \cdot \ln a_i \\
& + \frac{1}{2} \Big[\beta_{ll} \cdot \ln^2 p_{li} + \beta_{mm} \cdot \ln^2 p_{mi} + \beta_{cc} \cdot \ln^2 p_{ci} + \beta_{ff} \cdot \ln^2 u_{fi} + \beta_{pp} \cdot \ln^2 u_{pi} + \beta_{aa} \cdot \ln^2 a_i \Big] \\
& + \beta_{lc} \cdot \ln p_{li} \cdot \ln p_{ci} + \beta_{lm} \cdot \ln p_{li} \cdot \ln p_{mi} + \beta_{mc} \cdot \ln p_{mi} \cdot \ln p_{ci} + \beta_{pf} \cdot \ln u_{fi} \cdot \ln u_{pi} \\
& + \beta_{af} \cdot \ln a_i \cdot \ln u_{fi} + \beta_{ap} \cdot \ln a_i \cdot \ln u_{pi} .
\end{aligned}
\tag{5}
$$

with the input cost share equations

$$
S_l = \frac{\partial \ln C_i}{\partial \ln p_{li}} = \beta_l + \beta_{ll} \cdot \ln p_{li} + \beta_{lc} \cdot \ln p_{ci} + \beta_{lm} \cdot \ln p_{mi}
\tag{6}
$$

$$
S_c = \frac{\partial \ln C_i}{\partial \ln p_{ci}} = \beta_c + \beta_{cc} \cdot \ln p_{ci} + \beta_{lc} \cdot \ln p_{li} + \beta_{mc} \cdot \ln p_{mi}
\tag{7}
$$

$$
S_m = \frac{\partial \ln C_i}{\partial \ln p_{mi}} = \beta_m + \beta_{mm} \cdot \ln p_{mi} + \beta_{lm} \cdot \ln p_{li} + \beta_{mc} \cdot \ln p_{ci}
\tag{8}
$$

As in model I, the usual conditions for input price homogeneity and symmetry are imposed. The two models (1) - (4) and (5) - (8) allow different directions of analysing motorway renewal costs. While model I is a pure economic model allowing to analyse substitution elasticities and economies of scale in the process of renewing motorways, model II enables to analyse the influence which traffic volume and traffic composition have on the level and shape of the cost curve and to derive marginal costs for trucks.

Both types of translog models were estimated jointly with the cost-minimising input cost share functions. The estimation involved standardising each variable other than the factor shares, taking logarithms and dropping the last factor share equation by dividing the standardised costs and the labour and capital price by the standardised price of material. The system of equations which provides a seemingly unrelated regression model (SUR model) was estima-

ted by means of the constrained ML estimator within the SURE procedure of LIMDEP. This procedure guarantees maximum-likelihood estimates that are invariant with respect to which factor share equation is dropped (Barten 1969).

3.   Description of input data

The dependent variable, the renewal costs per motorway section, was constructed from two sources. First, the study had access to a data base with a detailed physical, non-monetary description of each renewal measure (length and type of measure, material used, thickness of layers concerned) for 1830 road sections of the German motorway network (see *ASTRA* 2001). This data, which excludes renewals of bridges and tunnels, is disaggregated for diffe-rent road layers and covers all measures taken within the last 20 years, in many cases even reaching back to the 50's and before. Second, unit costs at 2000 prices for each type of con-struction were used to express the physical description of the measures in monetary terms.[1] Further data treatment was necessary due to the fact that renewal expenditures are to a large extent investments rather than running expenditures, and their spending behaviour over time follows a cyclical pattern. The data base contained therefore only for a small percentage of sections renewal expenditures in single years. In order to obtain a more densely populated regression matrix and to smooth the cyclical pattern, the annual expenditures were summed up for the period from 1980 to 1999. The analysis refers to West German motorways only since extraordinary high maintenance and renewal expenditures spent in East Germany after the German re-unification would bias the results. The renewal data used for the econometric analysis in this paper amount to a fraction of about 70% of replacement expenditures for West German motorways (see *Kunert/Link* 1999).

The set of explanatory variables contains for each motorway section the factor input quanti-ties and input prices for labour, material and capital, the annual average daily traffic volume (AADT) of passenger cars and goods vehicles[2], the number of lanes, the type of material used

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[1] This working step was carried out by one of the leading engineering consultancies in the field of pavement management systems in Germany (SEP Maerschalk).

[2] Disaggregated traffic data for vehicle categories such as light goods vehicles, heavy goods vehicles with trailer, heavy goods vehicles without trailer, busses was only available for three single years (1990, 1993 and 1995) and only for a few federal states in Germany.

for renewal, the age of motorways at the beginning of the analysis period, the renewal expenditures before the analysis period and the climate conditions (table 1).

The factor inputs for labour and material were derived from the input quantities (material used and labour hours spent) used in the monetary valuation of physical renewal measures. Capital input was estimated by using regional data on capital stock for equipment in the construction sector. Input prices were derived from official regional statistics.

The traffic data was derived from automatic vehicle counting stations and refers to about 400 motorway sections. Gaps in the data due to failures of the devices and other reasons were closed as long as the share of necessary estimates was small enough not to bias the regression results. In order to account for the influence of maintenance and renewal practice in the past, two variables were introduced: one reflecting the renewal expenditures before the analysis period (as categorical variable due to problems with zero expenditures when taking logarithms), and another one indicating the age of motorway sections[1]. A set of dummy variables indicating the type of construction used for the renewals was introduced to control for the effect of more expensive types of renewal measures on the dependent variable.[2] Furthermore, expert opinion suggests that road damages are also caused by climate conditions (see for example *Hermansson* 2001, *Rübensam/Schulze* 1995), in particular by fluctuations of temperature around zero. Therefore, a variable "number of days with temperature fluctuations around zero" was constructed by using data from 260 climate stations.

The final data set contained 221 observations, e.g. substantially less cases than the original data (1837 observations) due to problems with missing or zero observations in one of the variables.

Table 2 shows the minimum and maximum values for the variables used and the mean and standard deviation. On average, DM mill. 1.95 (€mill. 0.997) was spent per motorway section for renewals during the period 1980-1999, (around €50000 per section and year). With these expenditures around 32000 sqm motorways were renewed. As the AADT figures for 1999

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[1] Ideally, the analysis should rather consider the number of years having passed since the last renewal. Since the data base does not contain a complete construction and renewal history for all sections it was not possible to construct such a variable. However, the age variable and the past maintenance variable reflect indirectly the influence of construction standards and quality as well as the traffic volume and composition anticipated in the design of motorways at the time of construction, and the renewal practice before the period of analysis.

[2] No cross-sectional data on the construction type at the beginning of the analysis period was available. It was thus not possible to analyse the impact of different construction types on the renewal cycle.

indicate, the West German motorways belong with an AADT of 26632 passenger cars and 5002 trucks to the highly utilised motorway networks in Europe.

4. Estimation results

Table 3 shows the estimation results for the translog models given in (1) – (4) and (5) – (8). To start with model I we can observe that almost all coefficients have the expected signs and are significant at 5% critical level. Exceptions are the interaction terms between labour and capital (not significant and wrong sign), between output and material (wrong sign) and the interaction coefficient β_{yl} (not significant). The input cost shares and the price elasticities of factor demand are positive, e.g. it is guaranteed that the estimated cost function is monotonous increasing and concave regarding the input prices.

Table 4 shows the *Allen-Uzawa* substitution elasticities between any pair of input factors

$$\varepsilon_{ij} = \frac{\beta_{ij} + s_{ij}}{s_i \cdot s_j} \tag{9}$$

and the own price elasticities of each factor demand

$$\varepsilon_{ii} = \frac{\beta_{ii} + s_i \, (s_i - 1)}{s_i^2} \qquad \text{with} \quad i = l, m, c \quad . \tag{10}$$

Material and labour are complementary factor inputs while capital and labour as well as material and capital are substitutes. However, the substitutability between material and capital is very low. A problem appears to be the value of -165 for ε_{ll} which might be due to the specification problems for β_{lc}, β_{ym} and β_{yl}. Furthermore, we can observe rather price inelastic factor demands with $|\varepsilon_{ii}|$ ranging from 0.17 to 0.48.

Returns to scale were calculated at the sample mean according to

$$RTS = \frac{1}{\varepsilon_y} = \frac{1}{\partial \ln C / \partial \ln Y}$$

$$= \frac{1}{\beta_y + \beta_{yy} \cdot \ln Y + \beta_{yl} \cdot \ln W_l + \beta_{ym} \cdot \ln W_m + \beta_{yc} \cdot \ln W_c} \tag{11}$$

They amount to 0.66 indicating considerable economies of scale in the renewal process of motorways.

Also for model II we can see that almost all parameters of interest have the expected signs and are significant at 5% critical level or at least at 10% level (table 3). Exceptions are the interaction term between labour and capital, the second-order term for the traffic volume of passenger cars and some of the material dummies. There is a problem regarding the properties of the cost function due to the fact that one input cost share is not positive. We will therefore not analyse and compare the input cost shares and the elasticities between the two models. The age variable including the second-order and interaction terms as well as the variable indicating past renewal levels were excluded from the original model (5) due to partly wrong signs and missing significance. The failure of specifying a model with age variables might be explained by the fact that the age variable was used as a rather indirect reflection of construction standards and design parameters anticipated in the original road design. Also the categorical variable indicating the level of past renewal expenditures could only serve as a proxy instead of the ideal measurement of the time period between two renewals at each single section. We also excluded the climate variable from the model due to wrong signs of the estimates and missing significance. Obviously, this variable was constructed from a too aggregated set of variables.[1]

Most important for pricing policy is to obtain estimates of marginal costs, in case of infrastructure damage costs in particular for goods vehicles and ideally further differentiated for different weight classes. Model II allows this type of analysis. However, because the study had no access to axle-load data, it is restricted to an average figure for goods vehicles. Figure 1 shows the cost elasticity

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[1] The level of disaggregation for the climate data was with 260 measurements much lower than those for the dependent variable (1837 motorway sections). The distance between climate stations and motorway section ranged from 3 km to 82 km with a mean of 25 km.

$$\frac{\partial \ln C}{\partial \ln u_f} = \frac{\partial C}{\partial u_f} \cdot \frac{u_f}{C} = \beta_f + \beta_{ff} \ln u_f + \beta_{fp} \ln u_p \qquad (12)$$

which expresses the relationship between marginal and average costs. This elasticity was calculated at the mean value of u_p and ranges from 0.05 to 1.17 with a digressively increasing shape. Multiplying this with an average renewal cost per truck of € 1.59[1] yields marginal costs per vehicle-km of trucks between €0.08 for the minimum AADT of trucks in the sample, €1.39 for the average AADT of trucks and €1.87 for the maximum AADT of trucks (figure 2). These cost estimates are for the lower and average utilisation level of roads below those obtained in *Lindberg* 2002 who derived within an engineering-based approach a cost elasticity between 0.1 and 0.8 and marginal costs between €0.77 and €1.86. The higher figures in *Lindberg* 2002 are explained by the fact that they were obtained from an ideal approach of assuming that renewals which are necessary from the engineering (or physical) point of view are indeed conducted. In contrast to this, the study presented in this paper is based on the actual renewal expenditures. The lower marginal costs in this paper reflect neglected maintenance and renewal in Germany especially in the 90es (see *Kunert/Link* 1999.

5. Conclusions

In this paper two translog models were estimated to analyse the cost behaviour of renewing motorways in Germany, based on observed spending during the 20 year's period from 1980 to 1999. The first model reflects the economic process of motorway renewals in terms of an output variable, measured as sqm renewed road, and factor input quantities and prices for material, labour and capital, while the second model establishes the relationship between the renewal costs and the use of infrastructure and factor inputs and prices. In our analysis we found substantial economies of scale in the renewal work. The conclusion from this is that the road authorities in Germany which tender the renewal tasks in specified lots to construction companies should think about a larger lot size as far as this does not cause to large traffic

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[1] This value was calculated from the data by assuming that all renewal costs are exclusively allocated to trucks. This assumption seems to be a plausible reflection of the road damage process and is also confirmed by the procedure in most European road accounts.

restrictions during the construction work. Furthermore, the modelling work revealed very low price elasticities of factor demands, complementarity between the input quantities for material and labour and substitutability between capital and labour and, though to a rather low degree, substitutability between material and capital.

With the second model we have estimated a cost elasticity as the ratio between marginal and average cost per truck-km. From this an important information for pricing policy, the marginal renewal cost per vehicle-km of trucks as part of optimal road user charges was derived. The estimates are lower than those obtained for renewal work on Swedish roads within an engineering-based study (see *Lindberg* 2002), and it can be concluded that the translog approach provides plausible estimates. The marginal cost result in this paper demonstrates clearly the differences between the two approaches. The engineering-based approach assumes that renewal measures which are from the engineering point of view necessary are indeed put into practice, and provides therefore an upper bound of estimates. The econometric approach is based on actual spending which might be below those necessary from an engineering perspective, and provides a lower bound of estimates. Although the findings in this paper confirm this relationship it would be useful to have for one single country results from both approaches since the comparison between Sweden and Germany might be biased to some (unknown) extent.

The value of the analysis presented in this paper can also be seen under practical aspects regarding data availability. The engineering approach requires cross-sectional, annual measurements of road conditions for a time horizon which is long enough to cover complete renewal cycles. This type of data is often hard to obtain. Although the data requirements for the translog approach are considerable too, this approach might be a useful alternative in cases were the measurement data for the engineering approach are not available.

Not unlike many econometric models a proportion of cost behaviour remains at the current stage unexplained. With improvements of the data base, in particular the inclusion of axle-load data and further explanatory variables, it is hoped that this problem can be solved. This holds also true for the desire to have marginal cost estimates for different weight classes of goods vehicles.

Appendix

Table 1: Description of input data

1. Dependent variable	• data on larger renewal measures for 1837 motorways sections during the period 1980-1999
2. Independent variables	
Factor inputs	• input quantities of labour, material and capital
Factor prices	• prices for labour, material and capital
Use data	• average daily traffic volume and mileages from counting stations for passengers cars and freight vehicles (400 sections) from 1990 to 1999
Type of renewal measures	• material used for the renewal measure (7 types of materials[1])
Road characteristics	• length of sections
	• number of lanes
	• age of sections
Maintenance information	• past expenditures (before 1980) on larger renewals for 1837 motorway sections
Climate	• number of days where temperature changed from below zero to above zero from 260 climate stations
	• number of days with snowfall
3. Cases used for the econometric analysis	221

[1] Bituminous concrete, bituminous mastic asphalt, bitumen binder, mastic asphalt with crushed materials, cement concrete, thin layer, others.

Sources: *ASTRA*, *SEP Maerschalk*, *BAST*, *DWD*, *DIW Berlin*.

Table 2: Descriptive analysis of German motorway data♣

Variable	Number of valid cases	Mean	Minimum	Maximum	Standard deviation
Renewal costs per section[1] (DM million)	221	1.95	0.01	11.17	2.25
	(1830)	(1.73)	(0)	(29.34)	(2.79)
Section length (km)	221	6.60	0.44	18.78	3.61
	(4138)	(4.48)	(0.031)	(23.03)	(3.44)
Number of lanes	221	2.39	2	3	0.489
	(4134)	(2.2)	(1)	(4)	(0.43)
Renewal costs before 1980 (DM million)	221	0.97	0	14.63	2.22
	(1243)	(0.99)	(0)	(18.76)	(2.37)
Climate variable[2]	221	429	152	688	106.96
	(4138)	(429)	(152)	(825)	(101.9)
AADT[3] passenger cars 1999	221	26632.2	1448	60642	12375.6
	(694)	(26395.9)	(1448)	(66488)	(130015.7)
AADT[3] trucks 1999	221	5001.6	384	11001	2354.7
	(693)	(4521.7)	(339)	(13378)	(2391)

♣) Figures in brackets refer to the full data set. –[1] Aggregated over a 20 years period (1980-1999). –[2] Number of days with temperature changes from above to below zero from 1990 to 1999. –[3] Annual average daily traffic volume.

Source: Own calculations.

Table 3: Regression results of the translog model for German motorway renewal costs

|	Model I				Model II			
	Coefficients	Standard deviation	t-value	Significance level	Coefficients	Standard deviation	t-value	Significance level
constant	2.057	0.0253	81.174	0.000	-1.996	0.0547	-3.652	0.000
α_1	-0.683	0.0233	-29.243	0.000	-1.682	0.0921	-18.265	0.000
α_2	-0.959	0.0486	-19.750	0.000	-1.985	0.1872	-10.604	0.000
α_3	-0.226	0.0149	-15.224	0.000	-0.638	0.0634	-10.076	0.000
α_4	-0.504	0.0132	-38.126	0.000	-1.391	0.0517	-26.897	0.000
α_5	-1.224	0.0287	-42.629	0.000	-2.560	0.1006	-25.430	0.000
α_6	-0.350	0.0189	-18.550	0.000	-0.7172	0.0745	-9.631	0.000
α_7	-0.078	0.0083	0.935	0.350	0.0589	0.0340	1.732	0.083
α_8	-0.179	0.0100	-1.794	0.073	-0.0361	0.0408	-0.886	0.376
δ_1	-	-	-	-	-0.0375	0.0551	-0.681	0.496
δ_2	-	-	-	-	-0.1139	0.0535	-2.130	0.033
δ_3	-	-	-	-	-0.0528	0.0459	-1.151	0.249
δ_4	-	-	-	-	-0.0716	0.0469	-1.523	0.128
δ_5	-	-	-	-	-0.2553	0.1342	-1.902	0.057
δ_6	-	-	-	-	-0.0179	0.0551	-0.326	0.745
δ_7	-	-	-	-	.[1]	.[1]	.[1]	.[1]
β_l	0.0028	0.0005-	6.008	0.000	0.0026	0.0002	17.266	0.000
β_c	0.1530	0.0114	13.429	0.000	0.6428	0.0112	57.392	0.000
β_m	0.8442	0.0113	74.476	0.000	0.3546	0.0112	31.732	0.000
β_y	0.8754	0.0253	48.383	0.000	-	-	-	-
β_f	-	-	-	-	0.1457	0.0553	2.637	0.008
β_{fp}	-	-	-	-	-0.1219	0.0517	-2.357	0.018
β_{ll}	0.0015	0.0001	10.349	0.000	0.0015	0.0001	11.358	0.000
β_{cc}	0.1088	0.0059	18.186	0.000	0.1228	0.0053	23.238	0.000
β_{mm}	0.1105	0.0059	18.660	0.000	0.1244	0.0053	23.638	0.000
β_{yy}	0.1193	0.0066	17.935	0.000	-	-	-	-
β_{ff}	-	-	-	-	0.3752	0.1002	3.745	0.000
β_{pp}	-	-	-	-	0.1434	0.1289	1.112	0.266
β_{lc}	0.0001	0.0002	0.803	0.422	0.00001	0.00009	0.193	0.847
β_{lm}	-0.0016	0.0002	-9.652	0.000	-0.0015	0.0002	-9.586	0.000
β_{mc}	-0.1088	0.0059	-18.300	0.000	-0.1229	0.0053	-23.301	0.000
β_{yl}	-0.00007	0.0002	-0.423	0.672	-	-	-	-
β_{yc}	-0.1099	0.0051	-21.453	0.000	-	-	-	-
β_{ym}	0.1099	0.0051	21.577	0.000	-	-	-	-
β_{pf}	-	-	-	-	-0.2644	0.1070	-2.471	0.014

[1] Excluded due to multicollinearity problems.

Source: Own estimations.

Table 4: Substitution elasticities and own price elasticities of factor demand

| Substitution elasticities[1]			
	Labour (W_L)	Capital (W_c)	Material (W_m)
Labour (W_L)	-165.019		
Capital (W_c)	1.063	-0.250	
Material (W_m)	-0.717	0.503	-1.026
Own-price elasticities of factor demand[1]			
	-0.479	-0.167	-0.335
[1] Calculated at the sample mean. Source: Own estimations.			

Figure 1: Cost elasticity (ratio between marginal and average costs) of trucks at German motorways
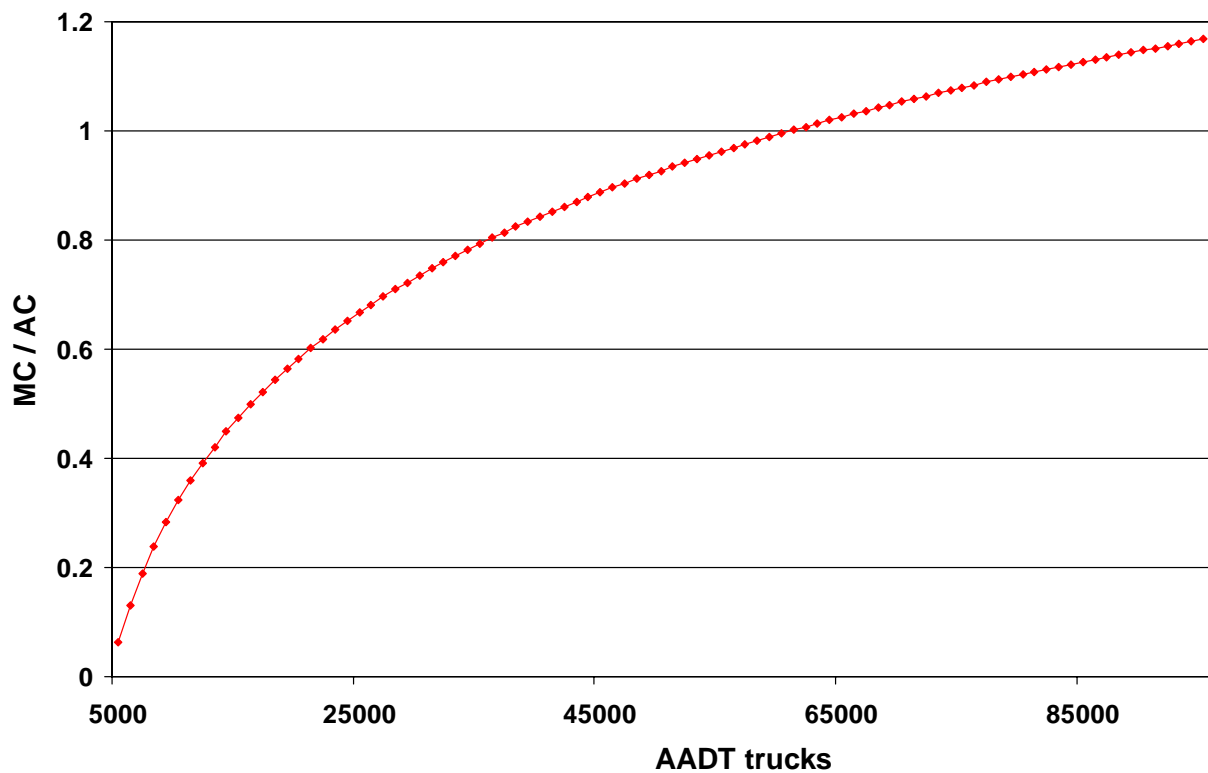
Source: Own calculations.

Figure 2: Marginal costs per truck-km at German motorways
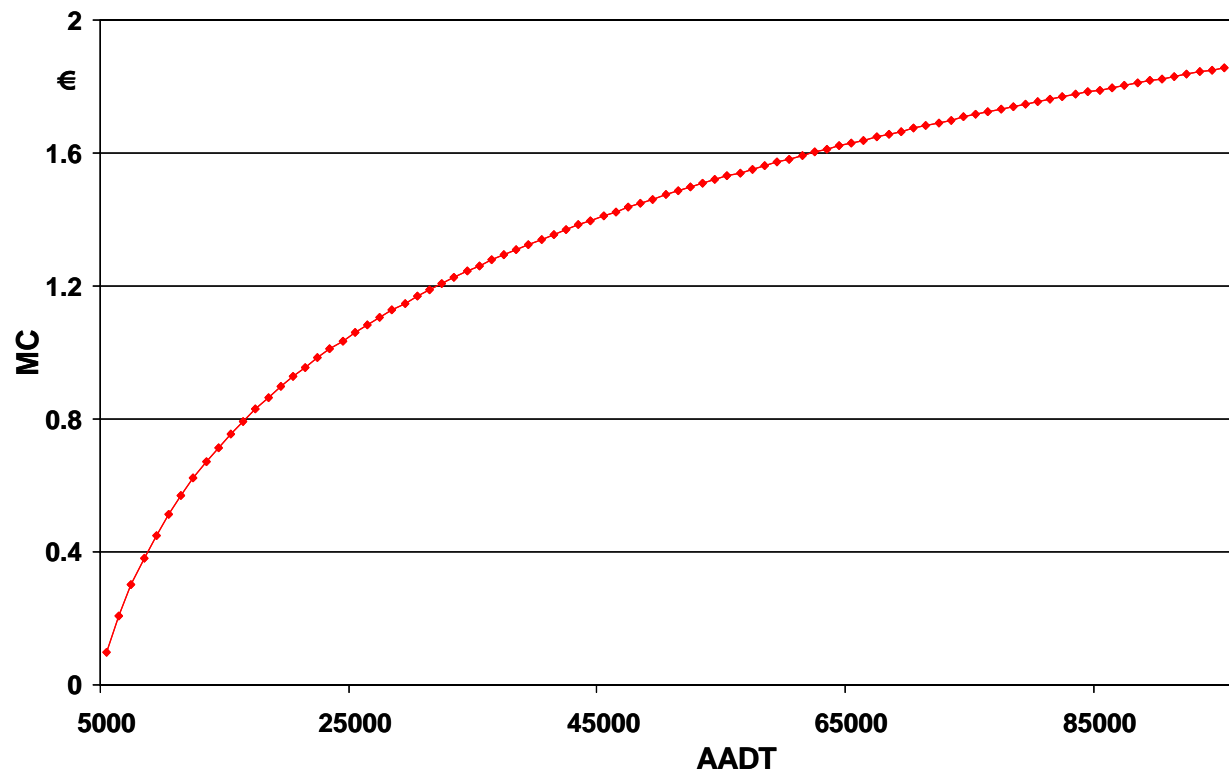
Source: Own calculations.

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