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An econometric analysis of motorway renewal costs in Germany

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Abstract

The analysis of motorway renewal costs presented in this paper was driven by two research questions: First, to analyse the economic process of motorway renewal work and to identify whether there exist economies of scale; and second to identify the influence of traffic volume on renewal costs and to derive an estimate of marginal infrastructure costs as part of optimal road user charges. The analysis is based on cross-sectional data for motorway renewal costs and traffic volume in Germany during the period 1980–1999. Two translog models were estimated, each of them including the factor input prices for labour, material and capital, and a set of regional dummy variables as well as dummy variables for the type of material used for renewal. The first model includes in addition to these variables the sqm of renewed road as explanatory variable. The second model was constructed to analyse the relationship between traffic volume and renewal costs and contains the average annual daily traffic volume of trucks and passenger cars as independent variables. Two main results were derived from the models: First, motorway renewal work is characterised by substantial economies of scale. Second, the relationship between renewal costs and traffic volume is expressed by a cost elasticity, i.e., the ratio between marginal and average costs, which ranges from 0.05 up to 1.17 with a digressive increase of marginal costs.

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1. Background

The analysis presented in this paper was driven by two research questions: First, charging for the use of infrastructure has become an important issue in transport policy and requires scientifically sound quantitative information on the level of charges to be raised. In this context, the marginal cost of road maintenance and renewal is one component of optimal prices for road use. A second issue to be dealt with in this paper refers to the economic properties of the motorway renewal process such as factor substitution and the existence of economies of scale.

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. For the available studies three main approaches can be identified. The majority of existing research follows an engineering approach and deals exclusively with the costs of pavement resurfacing. The basic idea of this approach is to analyse to what extent the life-time of a pavement is affected by traffic loads. The most prominent example of this approach is the AASHTO road test (Highway Research Board, 1961) in which variously loaded vehicles were driven on different types of road surfaces. The test concluded that the damaging power was approximately proportional to the fourth power of its loading (so-called fourth power rule). However, the opportunities to conduct large-scale experiments of this type are rather limited.[1] Therefore, Newbery (1988) has developed an analytical approach which is known as the so-called fundamental theorem. He has proven that under certain assumptions—no damaging effect of weather, equal age distribution of the roads, constant traffic flows—and for a condition-responsive maintenance strategy,[2] the marginal cost of pavement resurfacing is exactly equal to the average resurfacing cost and the road damage externality[3] is zero. This relationship provides a convenient shortcut which requires only few input data.[4]

In contrast to Newbery (1988) who applies assumptions and engineering experience on the design life of a road, Small and Winston (1988) as well as Small et al. (1989) use the cross-sectional measurements of road condition from the original AASHTO test data. They re-estimate the life-time of roads as the time-span between necessary resurfacings of road pavement in dependence of road thickness, traffic load and aging (weathering effect). Their main results are that

[1] Newbery (1988) estimates that a replication of the AASHTO road test would cost over $300 million at 1980 prices.

[2] A condition-responsive maintenance strategy means that the road authority decides to resurface any particular road when it reaches a predetermined trigger value of roughness.

[3] When a vehicle damages the road surface and increases its roughness, it thereby increases the vehicle operating cost of subsequent vehicles. This cost imposed on subsequent vehicles represents a road damage externality (see Newbery, 1988).

[4] However, introducing the weather effect into the model and allowing for changes in traffic volume imply that marginal resurfacing costs will be below or above average costs depending on the maintenance strategy adopted.

the life-time of roads is shorter than the AASHTO-based design life, and that the relation between pavement life and axle-load follows rather a third power law than the original fourth power law. Ozbay et al. (2001) use traffic data and information on time intervals between resurfacing dates and the year of analysis for individual OD pairs of the Northern New Jersey highway network to estimate marginal resurfacing costs. They base their estimates on traffic data measured as vehicles per day instead of axle-load data.

Lindberg (2002) provides an empirical test of Newbery's fundamental theorem based on longitudinal measurements of road condition from the Swedish Long-Term Pavement Management Programme. The model presented there allows for changes in traffic volume but assumes that all road damage is due to traffic (no weathering effect) and that the age of roads is equally distributed. It is demonstrated that the marginal cost of resurfacing an average road is a product of the average cost and an elasticity which expresses the changed life-time of pavement induced by changes in traffic load. In contrast to Newbery's fundamental theorem, Lindberg (2002) yields an elasticity which differs from unity.

A second stream of research refers to traditional cost allocation studies conducted within the context of public road accounts in Germany, Switzerland, Sweden and other countries. These studies 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 (for an overview see Link et al., 1999).

A third potential approach is to analyse cross-sectional data on observed spending for road maintenance and renewal by traditional economic approaches of cost function analysis. Attempts to estimate full systems of cost and factor input share equations have so far failed due to lack of cross-sectional data on factor inputs and input prices. Available studies for the road sector (Schreyer et al., 2002) and for rail infrastructure (Johansson and Nilsson, 2002; Gaudry and Quinet, 2003) argue that input prices do not vary across track sections or regions and estimate a cost equation only, either as log-linear models (Schreyer et al., 2002), translog models (Johansson and Nilsson, 2002) or as a Box–Cox model (Gaudry and Quinet, 2003).

Studies on the nature of the motorway maintenance and renewal process, the degree of factor substitution and the existence of economies of scale are rare, too. An example for an econometric analysis is provided in Talvitie and Sikow (1992). They use data on construction costs, factor inputs, input prices, road width and management types (share of contract work, etc.) and analyse the productive efficiency of highway construction work by means of frontier cost functions.[5]

The analysis presented in this paper employs a translog cost function approach to both problems. It makes use of a unique database consisting of cross-sectional data on motorway renewal expenditures, factor inputs and factor prices, sqm of renewed road and traffic volume in West Germany during the period 1980–1999. The paper is organised as follows: Section 2 discusses the methodological approach. Section 3 describes the input data used. Section 4 presents the estimation results and derives marginal renewal costs. Section 5 concludes.

[5] This work deals with the cost structure of constructing new highways and does not include any measure of traffic load. It can therefore not be used for deriving the marginal costs of infrastructure use.

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 and Christensen (1972) and Christensen et al. (1975), has remained to be the most frequently used form (for an overview of applications in transport, see Oum and 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 and 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 conceptual difference between the problem analysed in this paper and traditional cost functions employed so far in transportation research is the definition of the output variable. Almost all cost function studies in transportation analyse the cost structure of a whole industry such as the rail sector (including the track infrastructure), the trucking industry or the airline industry (for example Daughety et al., 1985; De Borger, 1992; Cantos, 2000). In the context of these studies, the output variable is straightforward defined as the traffic volume of different vehicle types measured as vehicle-km, train-km, gross-tonne km or passenger-km, which are produced by the companies of the industry through a combination of factor inputs such as energy, material, labour and capital. In contrast to these studies, this paper deals with two different problems: First, when analysing the economic properties of motorway renewal work (model I) it has to be borne in mind that the factor inputs used here are not those used for producing the mileage 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. For the second problem the core interest is to study the influence of traffic volume on the level of renewal cost (model II). Here it is obvious to define traffic volume as output variable, however, again the factor inputs used to produce traffic volume are not those employed to provide motorway renewals.

Model I analyses the economic process of renewing motorways as such. The renewal costs C_i are to be explained by the output variable Y_i defined as the sqm of motorways renewed at each section i over the analysis period, a vector of input prices $\mathbf{P}' = (p_l, p_m, p_c)$ for labour, material and capital and a set of dummy variables D_{ij} indicating the federal state j ($j = 1, \ldots, m$; $m = 8$), and M_{ik} representing the material used for renewals ($k = 1, \ldots, K$; $K = 7$, see Table 1). The model has the form

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

Table 1
Description of input data

1. Dependent variable	• Cross-sectional data on renewal measures 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	• Annual average daily traffic volume and mileages from counting stations for passengers cars and freight vehicles
Type of renewal measures	• Material used for the renewal measure (7 types of materials)[a]
Road characteristics	• Length of sections • Number of lanes • Age of sections
Maintenance information	• Past expenditures (before 1980) on larger renewals per motorway section
Climate	• Number of days where temperature changed from below zero to above zero from climate stations • Number of days with snowfall
3. Cases used for the econometric analysis	221

Sources: ASTRA, SEP Maerschalk, BAST, DWD, DIW Berlin.
[a] Bituminous concrete, bituminous mastic asphalt, bitumen binder, mastic asphalt with crushed materials, cement concrete, thin layer, others.

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

$$S_{li} = \frac{\partial \ln C_i}{\partial \ln p_{li}} = \beta_l + \beta_{ll} \cdot \ln p_{li} + \beta_{yl} \cdot \ln Y_i + \beta_{lm} \cdot \ln p_{mi} + \beta_{lc} \cdot \ln p_{ci}, \tag{2}$$

$$S_{ci} = \frac{\partial \ln C_i}{\partial \ln p_{ci}} = \beta_c + \beta_{cc} \cdot \ln p_{ci} + \beta_{yc} \cdot \ln Y_i + \beta_{lc} \cdot \ln p_{li} + \beta_{mc} \cdot \ln p_{mi}, \tag{3}$$

$$S_{mi} = \frac{\partial \ln C_i}{\partial \ln p_{mi}} = \beta_m + \beta_{mm} \cdot \ln p_{mi} + \beta_{ym} \cdot \ln Y_i + \beta_{lm} \cdot \ln p_{li} + \beta_{mc} \cdot \ln p_{ci}. \tag{4}$$

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

$$\sum_i \beta_i = 1, \quad \sum_i \sum_j \beta_{ij} = 0, \quad \sum_i \beta_{yi} = 0, \quad \text{and} \quad \beta_{ij} = \beta_{ji}, \text{ respectively,}$$

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 Section 3), the model does not allow to analyse possible changes of technologies for renewal measures.

The second model (model II) establishes the relationship between renewal costs and traffic volume and enables to derive marginal renewal costs as an input for welfare optimal charging schemes. We use here the annual average daily traffic volume (AADT) of trucks and passenger cars, denoted by u_{fi} and u_{pi}, as major explanatory variables, and keep also the vector of factor input prices for labour, material and capital required to carry out the motorway renewals. The underlying idea of this is that the damage caused by traffic loads is, amongst other factors such as input prices, age of motorways, climate conditions,[6] etc., reflected in the level of renewal costs. Apart from traffic volume, model II contains the renewal costs before the period of analysis, denoted by E_i (defined as categorical variable with the levels 0, 1, 2, 3), the age of motorway sections denoted by a_i, and the dummy variables from model I. The cost behaviour is then described as

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

with the input cost share equations

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

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

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

As in model I, the usual conditions for input price homogeneity and symmetry imposed.

The underlying theory of translog cost functions assumes that the economic entities behave as cost minimisers. Studies on the cost structure of publicly-owned entities such as railways or roads usually face the problem that this assumption is violated in practice. The renewal work at German motorways analysed in this paper is in the responsibility of the road administrations of the German federal states (länder) which are obliged to tender this task in order to guarantee it is carried out at lowest costs for the public. It seems therefore feasible to assume that this procedure comes close to a cost-minimising behaviour of the entities being in charge for maintaining and renewing motorways.

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 (e.g., dividing each variable by its sample mean), 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 estimated by means of the constrained ML estimator within the SURE

[6] Descriptive data analysis has shown that the climate variable seems to have no correlation with the level of renewal costs. This was also confirmed by wrong signs of the estimates and missing significance when including it nevertheless into the translog model presented in Eqs. (5)–(8). One reason might be that the climate variable had a too high level of aggregation. The distance between climate stations and motorway section ranged from 3 to 82 km with a mean of 25 km. For these reasons the climate variable is not presented in the model noted in Eqs. (5)–(8).

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 study used a database of 221 cross-sectional observations with an average length of motorway sections of 6.6 km. The dependent variable, the renewal costs per motorway section, was constructed from two sources: First, the study had access to a database with a detailed physical, non-monetary description of each renewal measure (length and type of measure, material used, thickness of layers concerned) per motorway section (see ASTRA, 2001). This data, which excludes renewals of bridges and tunnels, is disaggregated for different road layers and covers all measures taken within the last 20 years, in many cases even reaching back to the 1950s and before. Second, unit costs at 2000 prices for each type of construction were used to express the physical description of the measures in monetary terms.[7] 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 database 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.[8] 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 and Link, 1999).

The set of explanatory variables contains for each motorway section the factor input prices for labour, material (as a composite price obtained from specific prices for each type of material and the input quantities of material used for each section) and capital, the annual average daily traffic volume (AADT) of passenger cars and goods vehicles,[9] the type of material used 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).

Empirical information on input quantities spent by road construction firms is not accessible. However, the fact that the database contained a physical description of each renewal measure allowed to construct factor input quantities (working hours spent, quantity of material and equipment used). This was done by using road engineering expertise based on normative rules for each specific working step of a specific renewal measure, differentiated by type and thickness of road

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

[8] The original database covered around 1830 motorway sections. The share of sections where renewal measures were carried out in single years of the analysis period varied between 4% and 11%. Only sections which were renewed during the observation period were analysed.

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

Table 2
Descriptive analysis of German motorway data

Variable	Number of valid cases	Mean	Minimum	Maximum	Standard deviation
Renewal costs per section[a] (DM million)	221	1.95	0.01	11.17	2.25
Section length (km)	221	6.60	0.44	18.78	3.61
Number of lanes	221	2.39	2	3	0.489
Renewal costs before 1980 (DM million)	221	0.97	0	14.63	2.22
Climate variable[b]	221	429	152	688	106.96
AADT[c] passenger cars 1999	221	26,632.2	1448	60,642	12,375.6
AADT[c] trucks 1999	221	5001.6	384	11,001	2354.7

Source: Own calculations.
[a] Aggregated over a 20-year period (1980–1999).
[b] Number of days with temperature changes from above to below zero from 1990 to 1999.
[c] Annual average daily traffic volume.

layers and the type of material used. Input prices and wages were derived from official regional statistics. This procedure implies that the input quantities except the material input do not exactly correspond to the quantities really spent by construction firms but rather reflect normative input quantities. The advantage of this approach is that the bias which is usually contained in expenditure data can be avoided.[10]

The traffic data was derived from automatic vehicle counting stations. 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.[11] A set of dummy variables indicates the type of construction used for the renewals in order to control for the impact of more expensive types of renewal measures on the dependent variable.[12] Furthermore, expert opinion suggests that road damages are also caused by climate conditions (see for example Hermansson, 2001; Rübensam and 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.

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 €50,000 per section and year). With these

[10] According to expert opinion, firms often submit either too low or too high bids for renewal lots.
[11] Ideally, the analysis should rather consider the number of years having passed since the last renewal. Since the database 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.
[12] 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.

expenditures around 32,000 sqm motorways were renewed. As the AADT figures for 1999 indicate, the West German motorways belong with an AADT of 26,632 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 sign 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

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

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

$$\mathrm{RTS} = \frac{1}{\varepsilon_y} = \frac{1}{\partial \ln C / \partial \ln Y} = \frac{1}{\beta_y + \beta_{yy} \cdot \ln Y + \beta_{yl} \cdot \ln p_l + \beta_{ym} \cdot \ln p_m + \beta_{yc} \cdot \ln p_c}. \tag{11}$$

They amount to 0.66 and reveal considerable economies of scale. This result implies that larger lots tendered for renewal work would be economically preferable. Talvitie and Sikow (1992), which analyse construction costs of new highways in Finland, report a scale elasticity between 0.3 and 0.7. This indicates economies of scale of a similar magnitude like the result presented in this paper for renewal work.

Model II (Eqs. (5)–(8)) had to be modified in the estimation process. Both the age variable and the variable for past renewal levels had to be excluded from the original model (5) due to partly wrong signs and missing significance. The reason for these model failures might be that both variables served as proxies for actually preferred but not available measurements. The age variable was used as a rather indirect reflection of construction standards and design parameters anticipated in the original road design, and the variable for past renewal levels served as a proxy for the maintenance strategy instead of the ideal measurement of the time period between two renewals.

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

	Model I				Model II			
	Coefficients	Standard deviation	t-Value	Significant level	Coefficients	Standard deviation	t-Value	Significant 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	–	–	–	–	–[a]	–[a]	–[a]	–[a]
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_p	–	–	–	–	−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	0.0000	0.0001	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}	−0.0001	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_{fp}	–	–	–	–	−0.2644	0.1070	−2.471	0.014

Source: Own estimations.
[a] Excluded due to multicollinearity problems.

The final results for model II are summarised in Table 3. With a few exceptions (interaction term between labour and capital, second-order term for the traffic volume of passenger cars, some of the material dummies) the parameter estimates have the expected signs and are significant at 5% critical level or at least at 10% level. However, the negative sign for one of the input cost shares indicates that there is a problem regarding the properties of a well-behaved cost function

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

	Labour (p_l)	Capital (p_c)	Material (p_m)
Substitution elasticities[a]			
Labour (p_l)	−165.019		
Capital (p_c)	1.063	−0.250	
Material (p_m)	−0.717	0.503	−1.026
Own-price elasticities of factor demand[a]			
	−0.479	−0.167	−0.335

Source: Own estimations.
[a] Calculated at the sample mean.

(regularity, concavity, homogeneity). There are meanwhile several methods to treat this problem which the work presented in this paper shares with a number of empirical studies. Examples are eigenvalue decomposition methods and methods using Cholesky factorisation (Jorgensen and Fraumeni, 1981) which impose global curvature restrictions. However, this may lead to restrictions of flexibility and violations of underlying theory as Diewert and Wales (1987) show.[13] Other methods impose curvature restrictions locally (for example the numerical methods of Lau, 1978 and Gallant and Golub, 1984). More recently, a Bayesian approach has been applied to impose regularity conditions (Terrell, 1996; Kleit and Terrel, 2001).[14] An adoption of this technique to the data analysed in this paper remains an open and somewhat critical issue for future research. It should be borne in mind that the exclusion of (possibly larger) parts of the original data raises the question to what extent the results obtained are representative for the problem analysed.

Due to the problems with the properties of model II we will not analyse and compare the input cost shares and the elasticities between the two models. Rather we will focus on the core interest within model II, to analyse the impact of traffic volume on renewal costs and to derive estimates of marginal costs, in particular for goods vehicles. Since the study had no access to axle-load data, results are restricted to average figures for goods vehicles without disaggregation by weight classes. Fig. 1 shows the cost elasticity

$$\frac{\partial \ln C}{\partial \ln u_f} = \frac{\partial C}{\partial u_f} \cdot \frac{u_f}{C} = \beta_f + \beta_{ff} \ln u_f + \beta_{fp} \ln u_p, \tag{12}$$

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[15] 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 (Fig. 2).

[13] For example, results may be biased regarding the degree of input substitutability and own-price elasticities.
[14] In the Bayesian approach a prior is used to impose regularity conditions over a certain range of data points which allows to disregard that part of the posterior density that violates the underlying economic theory of the cost function.
[15] 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.

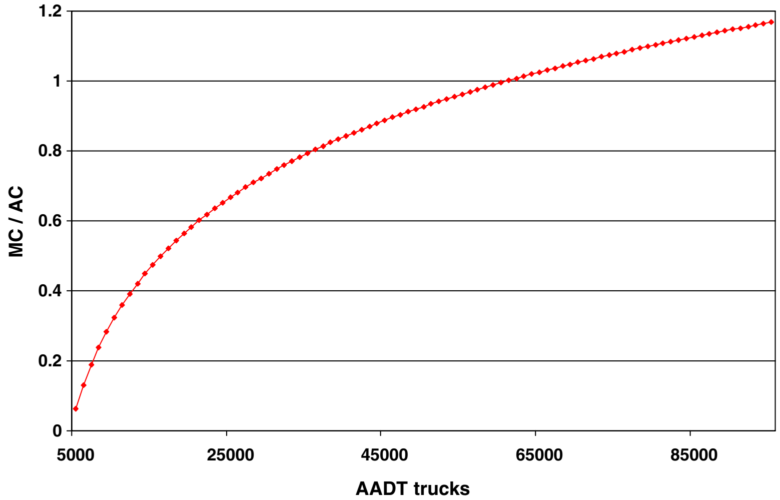

Fig. 1. Cost elasticity (ratio between marginal and average costs) of trucks at German motorways.

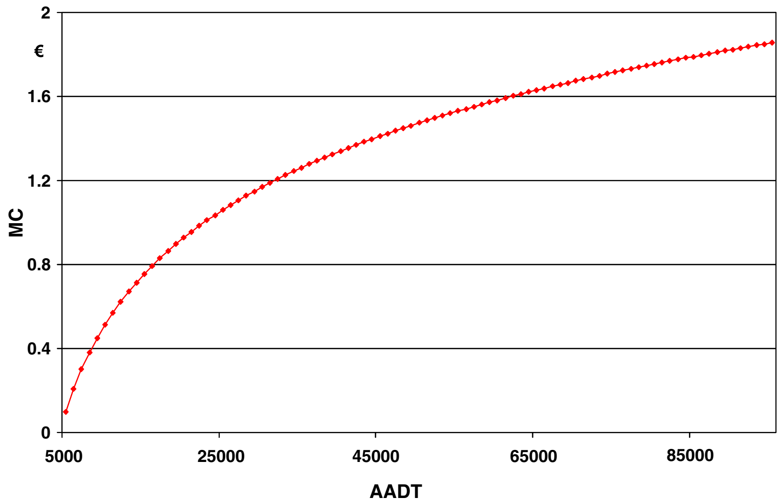

Fig. 2. Marginal costs per truck-km at German motorways.

Table 5 summarises available cost estimates from the studies mentioned in Section 1. A comparison of available estimates with the results presented in this paper is obviously hampered by differences in the approaches, in the scope of analysis (road network and traffic situation analysed), and by different units of expressing marginal costs (AADT versus ESAL km). In fact, the cost elasticity (MC/AC) is the only figure which can be used for discussing results from different studies. However, even here it has to be borne in mind that the results in this paper refer to the renewal process of all layers of a motorway while all other studies deal with pavement resurfacing costs.

The cost elasticity estimated in this paper has a magnitude which is comparable to results presented in Newbery (1988) (0.19–1.07, obtained by applying the fundamental theorem to Tunesian

Table 5
Overview of available estimates for marginal road infrastructure costs

Source	Scope of the study	Type of cost considered	Year/Time horizon	Price base	Marginal cost (MC) estimate	Cost elasticity MC/AC
Newbery (1988)	Tunisian roads	Cost of pavement resurfacing	n.a.	1983	0.13...2.58 US$/ESAL km	0.19...1.07
Newbery (1990)	UK road network	Cost of pavement resurfacing	1989/90	n.a.	0.035 pence/ ESAL km	n.a.
Small and Winston (1988)	US highways	Cost of pavement resurfacing	n.a.	n.a.	0.022...0.023 US$/ESAL mile	n.a.
Small et al. (1989)	US rural and urban freeways	Cost of pavement resurfacing	n.a.	n.a.	0.0148...0.0432 US$/ESAL mile	n.a.
Ozbay et al. (2001)	Highways Northern New Jersey	Cost of pavement resurfacing	2000	n.a.	0.062 US$/ vehicle mile	n.a.
Lindberg (2002)	Total road network Sweden	Cost of pavement resurfacing	1985–2000	2001	0.77...1.86 €Cents/v-km	0.1...0.8
This paper	Motorways West Germany	Total renewal cost (all road layers)	1980–1999	2000	0.08...1.87€/ v-km	0.05...1.17

roads), and to figures summarised in Lindberg (2002) (0.1–0.8, obtained by testing the fundamental theorem empirically with Swedish road data). Furthermore, the digressively increasing shape of the marginal cost curve is in line with results reported in Lindberg (2002). The estimates obtained for the marginal cost itself are higher than those presented in Lindberg (2002) who reports marginal costs between €Cents 0.77 and €Cents 1.86, and seem also to be higher than those presented in Ozbay et al. (2001).[16] The lower figures[17] in Lindberg (2002) can be explained by the fact that Lindbergs analysis refers to the Swedish road network which is characterised by lower utilisation levels than the German one, and deals exclusively with pavement resurfacing costs. Furthermore, Lindberg analyses the whole Swedish road network while the analysis presented here covers the motorways only which have the heaviest traffic loads and the highest costs. Apart from that, the rather high values are strongly influenced by the average cost figure which was calculated from the sample by assuming that all renewal costs are exclusively caused by trucks.

Finally, the digressive shape of the cost elasticity and the marginal cost curve presented in this paper are in contrast to the a priori expectation that in particular maintenance and renewal costs increase progressively with axle-loads as suggested by the AASHTO road test. A tentative explanation might be that the analysis presented here had no access to axle-load data but used mileages of trucks instead. Furthermore, the econometric model was based on observed spending which does not necessarily correspond directly with road damages as measured within the AASHTO road test.

[16] A comparison with results from the other studies from Table 5 is not possible since these are expressed in ESAL km.

[17] Actually, one would expect that marginal costs obtained with an engineering-based approach are higher than those estimated with an econometric model because the engineering-based approach can be considered as 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.

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 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. The second model establishes the relationship between the renewal costs, 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 chose a larger lot size as far as this does not cause unacceptable traffic 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.

The main result from the second model is an estimate for the cost elasticity, e.g., the ratio between marginal and average cost per truck-km. From this, an important information for pricing policy, the marginal renewal cost per truck-km as part of optimal road user charges was derived. The cost elasticity obtained from the model has a magnitude which is comparable to results in Newbery (1988), Lindberg (2002) and Schreyer et al. (2002). Furthermore, the gradually increasing marginal cost curve corresponds well with findings from Lindberg (2002). However, the marginal cost estimates are higher than those reported in other studies. There are various reasons for this, ranging from differences in the approaches used, the type of road network and traffic situation analysed, and the scope of costs included into the models. A direct comparison of marginal cost estimates from different studies is therefore not recommended, neither is a transfer of marginal cost figures from one context to another. For the purpose of comparison of results and their use in pricing policy it seems more plausible to transfer the cost elasticity as the ratio between marginal and average cost.

The marginal cost curve derived in this paper does not reflect the well-known fourth power rule obtained within the AASHTO road test (see Highway Research Board, 1961). Two reasons might explain this: First, the study had no access to axle-load data but used the AADT of trucks instead, e.g., it was not possible to model directly the deterioration process of roads caused by axle-loads. Second, in contrast to the AASHTO road test where damages were measured, this study was based on observed spending for renewal measures, which do not necessarily correspond directly with road damages.

The value of the analysis presented in this paper can also be seen under the aspect of data availability. The engineering approach requires cross-sectional, annual measurements of road condition 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 where the measurement data for the engineering approach are not available.

Not unlike many econometric models a proportion of cost remains unexplained at the current stage. This and some estimation problems (one negative input cost share in model II) call for further research with improved data. Necessary improvements of the database refer especially to the availability of axle-load data, which would enable a more realistic reflection of the road damage process. Further explanatory variables such as the time passed since the last renewal and more spatially disaggregated climate data could contribute to this.

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