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On the Difficulties to Calculate Infrastructure Charges for Heavy Goods Vehicles

A Review of 15 Years' Experience in Germany

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Abstract

This paper analyses the calculation principles used for determining the level and differentiation of HGV charges in Germany. It demonstrates that calculating average cost-based charges is far from straightforward, even with an agreed methodology, and involves sensitive methodological choices. Based on a review of available studies, the paper argues that estimating marginal costs does not necessarily involve more complexity than the approach used for calculating average cost-based charges. Moving towards social marginal cost-based charging would foster a more efficient use of resources and road capacity, and (fully) including congestion, environmental, and noise costs enables sufficient revenue to recover infrastructure costs.

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1.0 Introduction

Throughout his career, Brian Bayliss maintained a strong interest in European transport policy, particularly as it relates to the road haulage industry. He fully recognised the importance of road user charges for the efficient functioning of the Single Market in road haulage (see, for instance, Bayliss and Millington, 1995). Against this background, this paper in honour of Brian Bayliss deals with the calculation of both average and marginal cost-based road user charges for heavy goods vehicles in Germany.

Since the Green Paper of 1995 (CEC, 1995) and its successors (CEC, 1998, 2001), EU transport policy has attempted to reconcile transport prices with the social marginal costs of transport. Heavy goods vehicles (HGVs) have played a central role in this policy due to their importance in cross-border transport. This is reflected in a series of EU directives (directives 1999/62/EC, 2006/38/EC, and 2011/76/EC), which set common rules for levying HGV charges — aimed at moving from time-based to distance-based schemes, and from exclusively infrastructure cost-related tolls to charges that reflect (parts of) environmental, noise, and congestion costs. According to the aforementioned EU directives, charges shall be based on the full recovery of infrastructure costs, and be related to the cost of construction, operation, maintenance, and development of the roads concerned. They may also include a return on capital and/or a profit margin that is based on market conditions. Furthermore, HGV charges are allowed to vary according to air pollution, noise, and congestion costs, but these variations shall not exceed the charge in the respective lowest charge class by a predefined percentage.¹

Germany was one of the first² EU member states that introduced kilometre-based HGV charges. Meanwhile, Germany looks back at a 15-year history of distance-based HGV charging. This long experience, both in terms of underlying calculation studies for determining the level and structure of charges, and the potential for analysing observed impacts of charging, constitutes an interesting case for analysis.

The starting point for this paper is the apparent discrepancy between the aforementioned HGV charging directives and the goal to charge transport users the social marginal cost they cause, as proposed in a series of EU Green and White papers (CEC, 1995, 1998, 2001). First, the charging directives for road freight transport ties HGV charges to average costs instead of (short-run) social marginal costs. Second, the extent to which the overall charge level can reflect environmental, noise, and congestion costs is capped by the aforementioned percentage. There are several reasons for this discrepancy and, indeed, the tension between social marginal cost pricing as the efficient pricing rule, and average cost pricing as the most popular pricing rule to finance infrastructure, has been present in the economic debate since Dupuit and Pigou³ — more recently debated in Rothengatter (2003, 2018) and Nash (2003).

¹Air pollution charges shall not exceed the charge in the cleanest emission class by more than 100 per cent. Congestion charges shall not exceed the maximum level of the weighted average charge by more than 175 per cent and shall only be charged for at a maximum 5 hours of peak periods.

²The non-EU country Switzerland introduced, already in 2001, a distance-based HGV charge. Austria followed in 2004.

³The discussion on the 'right' base for charging dates back almost a century, with Clark (1923) probably being one of the first authors discussing the caveat of marginal cost pricing to recover full costs. One of the milestones in this discussion was the work of Coase (1946), which gave the name 'The marginal cost controversy'.

Presumably, the major reason for adopting an average cost principle for charging HGVs in the EU was the aim of achieving cost recovery, which cannot be met by a marginal cost pricing scheme restricted to infrastructure costs. In addition, member states assumed problems in transit freight traffic where national governments might have incentives to charge transit traffic above marginal costs, causing inefficient detouring as well as distortions to production and distribution decisions. Furthermore, calculating and supervising the adequacy of average cost-based charges was assumed to be less complicated and estimates easier to replicate than marginal cost calculations involving more complexity. The EU directives on HGV charging might thus be viewed as a compromise to make the schemes acceptable to member states and to achieve progress from the former time-based EuroVignette to distance-based schemes that are closer to marginal cost pricing.

Given the calculation rules in the aforementioned EU directives, one would assume that calculating average cost-based HGV charges can hardly involve a great deal of methodological and empirical difficulties, in contrast to marginal cost estimation. In practice, this appears not to be true, as this paper demonstrates. This paper is placed in the context of the debate on calculation complexity and cost recovery of average cost charges versus marginal cost-based charges for HGV. It discusses the calculation principles and sensitive methodological choices for HGV charges in Germany, and compares the results from the available four toll calculation studies — all of them applying a presumed equivalent methodology. Furthermore, this paper reviews the state of research in estimating marginal road infrastructure costs, and discusses the complexity of both average and marginal cost estimation. Given the original character of HGV tolling as charging for infrastructure costs, this discussion is restricted to the cost of construction, operation, maintenance, and renewals.

The remainder of this paper is organised as follows. Section 2 analyses the cost calculations used to determine the level and structure of HGV charges in Germany since 2005, with a focus on the pure infrastructure cost part. Section 3 summarises the available literature on estimating marginal road infrastructure costs. Section 4 discusses the impacts from the average cost-based current scheme versus expected impacts of moving towards a social marginal cost-based scheme. Section 5 concludes.

2.0 The Methodology Used for Calculating HGV Charges in Germany

Road freight vehicles (from Germany and from abroad) using German motorways have been subject to distance-based road user charges for 15 years. The charging scheme was launched in 2005 as a GPS/GPN-based electronic toll collection scheme, and was applied to vehicles with a maximum gross weight of 12 t and more on motorways (Autobahnen with a network of around 13,100 km) — as well as on a set of federal roads⁴ that were assumed to be used as detouring alternatives. Since 2015, freight vehicles from 7.5 t upwards have been tolled and, since 2019, tolling has been extended to all federal roads (Bundesstraßen with a network length of around 37,900 km). Based on the respective EU directives (1999/62/62 EC; 2006/38/EC, and 2011/76/EU), the German HGV charge

⁴Around 270 km of so-called Bundesstraßen, extended in August 2012 and July 2015 by 1,100 km at any one time.

is aimed at recovering the full costs of construction, maintenance, and operation of motorways attributed to goods vehicles, including the cost of operating the charging scheme. Until 2015, the charge level varied by two classes of axle configurations and, since then, by four classes. Furthermore, charges varied by three — and since 2009 by four — emission classes. Since 2015, an additional km-based charge for air pollution costs has been raised. In 2019 a noise charge was added, and due to the expansion of tolling to vehicles with a weight from 7.5 t upwards, the differentiation of the pure infrastructure charge was changed into a combination of vehicle weight and number of axles, while leaving the total of four charge levels (Table 1).

Infrastructure costs caused by HGVs comprise capital costs (depreciation and interest) of the network, running costs for operation and maintenance, administration and police costs, and the costs of operating the HGV tolling system. These costs made up the sole part of the charge until 2014 and have remained by far the largest part of the charge since then. The German government has decided to apply a forward-looking approach, which forecasts infrastructure costs for a five-year period, based on the justification that the cost of future reinvestment cycles, as well as planned network expansions, have to be recovered. The calculation procedure consists of three major steps, each of them involving sensitive methodological decisions and choices of sensitive parameters:

- derivation of the capital value and calculation of depreciation and interest;
- definition and calculation of running costs; and
- allocation of total costs (the sum of capital costs and running costs) to vehicle categories.

This paper analyses the four available road infrastructure cost studies conducted for calculating the level and differentiation of HGV charges in Germany: Prognos and IWW (2002) for the period 2003–7,⁵ Prograns and IWW (2007) for the period 2008–12, Alfen *et al.* (2014) for 2013–17, and Alfen *et al.* (2018) for 2018–22.

2.1 Capital stock value and depreciations

For calculating the value of the capital stock, a choice has to be made between two approaches: these are the direct method, sometimes also referred to as the synthetic method; and the indirect method, also referred to as the cumulative or perpetual inventory method (PIM). Calculating the capital stock with the PIM is based on ‘estimating how many of the fixed assets installed as a result of gross fixed capital formation undertaken in previous years have survived to the current period’ (UN, 2020). While the PIM is the most commonly used tool in the Systems of National Accounts (SNA) of most OECD countries, the official German road infrastructure cost accounts employ the synthetic method, which is supposed to measure the capital value more precisely due to its ability to include a more differentiated set of asset categories.

The basic principle of the direct method is to compile an inventory of assets in physical units and to value them by unit costs. The German road infrastructure cost accounting is based on such an inventory for all road sections, which are described by length, width, number of lanes, age, type of construction, existence of bridges and tunnels, type of

⁵Due to technical and organisational problems with the tolling system, HGV charging started only in 2005.

Table 1
HGV Charges in Germany

Year	Weight and axle configuration	Emission class						
		A	B	C	D	E	F	
2005–7	Vehicles with a maximum GVW of 12 t and more							
	Up to 3 axles	0.090	0.110	0.130	–	–	–	
	4 axles and more	0.100	0.120	0.140	–	–	–	
2007–8	Vehicles with a maximum GVW of 12 t and more							
	Up to 3 axles	0.100	0.120	0.145	–	–	–	
	4 axles and more	0.110	0.130	0.155	–	–	–	
2009–14	Vehicles with a maximum GVW of 12 t and more							
	Up to 3 axles	0.141	0.169	0.190	0.274	–	–	
	4 axles and more	0.155	0.183	0.204	0.288	–	–	
Jan.–Sep. 2015	Vehicles with a maximum GVW of 12 t and more			Infrastructure charge				
	Up to 3 axles			0.125				
	4 axles and more			0.131				
		0.000	0.021	0.032	0.063	0.073	0.083	
				Air-pollution charge				
Oct. 2015–18	Vehicles with a maximum GVW of 7.5 t and more			Infrastructure charge				
	2 axles			0.081				
	3 axles			0.113				
	4 axles			0.117				
	5 axles and more			0.135				
			0.000	0.021	0.032	0.063	0.073	0.083
				Air-pollution charge				
Since 2019	Vehicles with a maximum GVW of 7.5–11.99 t, all axle configurations			Infrastructure charge				
	12–18 t, all axle configurations			0.080				
	18 t, up to 3 axles			0.115				
	18 t, 4 axles and more			0.160				
					0.174			
			0.011	0.022	0.032	0.064	0.074	0.085
				Air-pollution charge				
				Noise charge				
				0.020				

geography, and so on. For the evaluation of assets, different types of assets are distinguished such as land, earthwork, different road layers (frost protection layer, base and binder course, surface), equipment, bridges, tunnels, and other assets. The most sensitive parameter in these calculations is the choice of unit costs, which express the replacement value of the respective asset type. They are not readily available from official

Table 2
Capital Stock Values and Depreciation (€ bill.) for German Motorways and Federal Roads

<i>Source</i>	<i>Year</i>	<i>Method</i>	<i>Gross capital stock*</i>	<i>Net capital stock*</i>	<i>Depreciation</i>
<i>Motorways</i>					
Prograns and IWW (2007)	2013	synthetic	163.74	100.11	3.37
Alfen <i>et al.</i> (2014)	2013	synthetic	157.55	96.90	1.83
Transport in figures	2013	PIM	148.30	103.00	2.63
Alfen <i>et al.</i> (2014)	2015	synthetic	153.15	98.26	1.94
Transport in figures	2015	PIM	154.30	106.40	2.76
<i>Federal roads</i>					
Prograns and IWW (2007)	2013	synthetic	172.10	80.96	2.82
Alfen <i>et al.</i> (2014)	2013	synthetic	165.73	98.06	1.94
Transport in figures	2013	PIM	105.30	69.10	1.92
Alfen <i>et al.</i> (2014)	2015	synthetic	170.87	97.76	2.04
Transport in figures	2015	PIM	107.90	70.39	1.98

*Excluding land value.

statistics but have to be derived from engineering regulations for some types of assets, while they are based on expert estimates and judgements for others. Due to the summation of all evaluated assets over all sections, small errors in the choice and estimation of unit costs can contribute to considerable deviations of the estimated value from the true (unknown) value.

In the next step, the annual amount of depreciation is derived as the difference between the replacement value of the asset at the beginning and the end of the year.

Table 2 shows estimates for the capital stock and depreciation obtained with the synthetic method applied by different consultancy teams, and the figures obtained with the PIM. Most striking is that the figures do not only differ between the synthetic method and the PIM, which can be explained by methodological differences, but also between the calculations with the synthetic method when performed by different consultancy teams. The difference of results for the gross capital stock, obtained with the synthetic method and the PIM, respectively, is particularly high for federal roads.

With the synthetic method, Prograns and IWW (2007) obtain a more than 63 per cent higher capital stock than the one obtained when applying the PIM; Alfen *et al.* (2014) calculate a 57 per cent higher figure. For motorways, the difference between the synthetic method and PIM is at the level of 5 to 10 per cent. A striking result is that, by applying the synthetic method, Alfen *et al.* (2014) obtain a 4 per cent lower capital stock value for both motorways and federal roads than Prograns and IWW (2007), but by a 21 per cent higher net capital stock for federal roads. Furthermore, the magnitude of results for depreciations is remarkable without any clear pattern. Prograns and IWW (2007) obtain depreciations, which are for motorways by 28 per cent and for federal roads by 47 per cent higher than those obtained with the PIM. Alfen *et al.* (2014, 2018) yield for motorways only 70 per cent of the respective figure from the PIM, but for federal roads roughly the same value as the PIM. While methodological issues can be blamed for these differences, there is no explanation for the different results within the synthetic method. Alfen *et al.* (2014) arrive in their study for the year 2013 at only 54 per cent and

Table 3
Main Results from German HGV Toll Calculations (in Bill. €)

Year	Capital stock ¹		Capital costs	Out of these Depreciation	Running costs	Out of these		Infrastructure costs		
	Gross	Net				Police costs	Tolling system	Total	Tolled vehicles	Charge per vkm
<i>Prognos and IWW (2002)</i>										
2003	123.8	75.8	5.34	2.31	2.17	n.a.	0.56	7.51	3.40	0.15
2005	127.9	77.4	5.75	2.43	2.28	n.a.	0.56	8.03	3.62	0.15
2010	135.4	80.9	6.72	2.71	2.58	n.a.	0.56	9.30	4.13	0.16
<i>Prograns and IWW (2007)</i>										
2005	164.0	111.5	7.28	2.82	2.25	n.a.	0.62	9.53	4.08	0.16
2007	169.5	114.1	7.96	2.90	2.60	n.a.	0.84	10.57	4.72	0.17
2008	172.1	114.9	8.40	3.07	2.59	n.a.	0.77	10.99	4.84	0.17
2010	177.3	116.7	9.06	3.15	2.69	n.a.	0.75	11.74	5.20	0.17
2012	182.8	119.1	9.93	3.37	2.81	n.a.	0.75	12.74	5.65	0.18
<i>Alfen et al. (2014)</i>										
2013	169.1	108.4	3.67	1.83	2.96	0.73	0.77	3.05	26.49	0.12
2014	172.7	109.4	4.21	1.89	2.92	0.73	0.75	3.28	27.38	0.12
2015	176.5	110.6	4.76	1.94	2.97	0.73	0.77	3.56	28.18	0.13
2016	180.3	112.2	5.34	2.00	2.99	0.73	0.76	3.83	29.07	0.13
2017	184.2	113.5	5.91	2.06	2.99	0.73	0.76	4.11	30.07	0.14
<i>Alfen et al. (2018)²</i>										
2018	377.8	245.4	11.53	3.43	3.89	1.11	0.96	6.46	39.34	0.16
2019	385.7	247.9	11.73	3.55	3.99	1.13	0.99	6.67	41.93	0.16
2020	393.8	250.6	11.94	3.67	4.02	1.16	0.95	6.67	41.93	0.16
2021	402.4	253.7	12.17	3.80	4.13	1.18	0.99	6.67	41.93	0.16
2022	410.9	256.5	12.40	3.93	4.22	1.20	1.01	6.67	41.93	0.16

¹ Including land value. ² Figures refer to the total of motorway and other federal roads since 2018, and are thus not comparable with the figures in preceding years.

69 per cent of depreciations for motorways and federal roads, respectively, from those calculated by Prograns and IWW (2007). Finally, it should be noted that the need to forecast capital stock values and depreciation for a five-year period introduces some degree of uncertainty, even for such rather slowly developing economic indicators. The second road cost study (Prograns and IWW, 2007) corrected the capital stock of motorways by 28 per cent and by 31 per cent upwards for 2005 and 2010, respectively, accompanied by an increase of depreciation costs by 16 per cent in both 2005 and 2010 (see Table 3).

2.2 Approaches for calculating interest on public capital

While there has been a long-standing discussion in Germany on whether road infrastructure costs should contain interest on capital at all (see Brenner, 1997; Holocher, 1998 arguing against; Link *et al.*, 2009 arguing in favour), the road cost accounts for calculating HGV charges have included this element. Interest on capital make up more than half, and sometimes even more than two-thirds of total capital costs (Tables 2 and 4), indicating that

Table 4
Interest Rates and Depreciation in the German Road Cost Accounts

Year	Approach	Interest rate (%)	Depreciations (bill. €)
<i>Prognos and IWW (2002)</i>			
2003 (base year)	Opportunity cost approach	4.0	3.03
2005		4.3	3.32
2010		5.0	4.01
<i>Progrtrans and IWW (2007)</i>			
2005 (base year)	Opportunity cost approach	4.0	4.46
2007		4.4	5.06
2008		4.6	5.33
2010		5.1	5.91
2012		5.5	6.56
<i>Alfen et al. (2014)</i>			
2013 (base year)	Opportunity cost approach	1.7	1.84
2014		2.1	2.32
2015		2.5	2.82
2016		2.9	3.34
2017		3.4	3.86
<i>Alfen et al. (2018)</i>			
2018–2022*	Opportunity cost approach	3.3	8.28

*Calculations relate to the total of motorways and federal roads. The amount of calculated depreciations are therefore not comparable.

the choice of approach is one of the sensitive decisions in road infrastructure cost accounting. The choice of an appropriate calculation approach depends on the type of roads provider — that is, the involvement of private or public funds. Public funding of roads in Germany implies that a social discount rate (SDR) has to be chosen. It should also be noted that using the synthetic method for capital stock valuation leads to values at nominal prices, and thus the discount rate for calculating interest has to also be at a nominal base.

The rationale for a social discount rate is derived from two theoretical arguments leading to two distinct measurement approaches. The first one is the argument of opportunity costs that arise when binding capital in public sector assets — that is, replacing either private consumption or private investment projects. This perspective leads to the social opportunity cost of capital (SOC) approach, which is traditionally based on the rate of return foregone when resources are withdrawn from the private sector (see Baumol, 1968, 1969; Harberger, 1972). The empirical estimation requires information on the rate of return that private firms wish to achieve on marginal low-risk investments. The argument behind this is that public investment projects displace private investment and/or private consumption at the margin. Deriving the SOC depends on the assumption regarding the type and shares of displacement. Displacing private consumption implies that private households give up consumption for which they were willing to reduce their savings at the margin and face foregone interest. The SOC can be derived from the interest of risk-free (usually) public loans. Displacing private investment means that a private actor will

give up those projects with the lowest return, and the SOC can be derived from the risk-free market return of marginal private investments.⁶

The second approach is the social time preference (STP) approach, which is based on utility arguments. The STP reflects the consumption side and equals the marginal rate of substitution between consumption in the present period t and the subsequent period $t + 1$. It expresses how many units of consumption in one period have to be offered to consumers to make them sacrifice one unit of consumption in the period before — that is, it measures the rate at which individuals collectively trade off present and future consumption. There is a vast body of literature to derive the STP, which will not be reviewed in this paper. To summarise the principle in brief, the standard formula for determining the social time preference rate is given by the Ramsey formula (Ramsey, 1928), where the discount rate consists of the pure time preference rate — plus the product from the elasticity of marginal utility of consumption and the per capita growth rate of consumption. Estimates for these parameters are available but show a considerable bandwidth. While the per capita growth rate of consumption is conceptionally relatively easy to measure (although required to be forecasted), the pure time preference rate is more controversial, subject to ethical considerations, and hardly amenable to empirical analysis. Often it is subject to expert opinions, whereby the views on the weight given to future populations differ (see Koopmans, 1965; Solow, 1974; Arrow *et al.*, 1996; Cline, 1999; Stern, 2006). The value for the elasticity of marginal utility of consumption has proven to be controversial too. There are three potential empirical approaches (see Groom and Maddison, 2013, for an overview including the bandwidth of estimates), which include the equal sacrifice approach using income tax data, life-cycle models of intertemporal household's behaviour, and subjective well-being approaches based on population surveys on life satisfaction.

In a first-best situation of an optimal intertemporal allocation between investment and consumption, both rates are equal. However, the existence of distortionary taxes, imperfect information, risk-premiums for private investments, and other reasons led to deviations from the optimal level of investment, and, therefore, the results from the two approaches will diverge. This raises the question how to choose a measure for discounting in a second-best world, and indeed there has been an intensive debate on the appropriate choice of SDR (see Arrow *et al.*, 1996) and on how to explain the different results from the two approaches. One important issue to account for is the existence of distortionary taxes, as mentioned above. Another issue that might provide explanations for the different values obtained with the two approaches is that there are distributional issues in trading-off present versus future consumption in the STP approach, combined with potential under-saving (see Boadway, 2006). In general, both the SOC and the STP approach face the problem of quantifying the degree to which public investment displaces private projects.

Apart from the aforementioned general debate on whether road user charges should contain interest on capital at all when roads are provided by state (tax) funding, there

⁶The fact that for both an assumed displacement of private consumption and private investment risk-free loans, and risk-free market returns, are used does not mean that public investments do not involve any risk. This is in some countries treated directly by adjusting the discounting rate. However, there are also arguments that discounting is an instrument to homogenise different streams of costs and benefits over time, while risk should be considered separately by calculating risk-adjusted cost and benefit equivalents.

had never been a scientific debate in Germany on the choice between the SOC or the STP approach until the road cost account for the 2014–17 period. The preceding studies (that is, Prognos and IWW (2002) and Prograns and IWW (2007)), chose interest rates ranging from 4.3 per cent (2005) to 5.5 per cent (2012) derived from capital market interest, but do not explicitly give references to which types of public or private loans these rates refer to (Table 3). While their figures indicate the use of the opportunity cost approach, Doll and Schaffer (2007) argue that the German CBA discount rate was 3 per cent at that time, which would lead to the figures mentioned above when adding the forecasted inflation rate. It should be noted that this discount rate of 3 per cent was derived from an intertemporal model, which optimises the choice between consumption and investment (Kotz *et al.*, 1987) — that is, it was based on a first-best solution where SOC and STP were equal.⁷ Meanwhile, the official German CBA framework for transport projects is now based on a considerably lower social discount rate of 1.7 per cent. This rate is based on Beckers *et al.* (2009), who calculated both the SOC and the STP with a bandwidth of parameter values from international studies, and arrived at a plausible rate of 1.7 per cent.

The rather high interest rates, in particular at the end of the second tolling period (Prograns and IWW, 2007), did not reflect the decrease of interest rates on capital markets since 2008. Consequently, the European Commission criticised the level of calculated interest as excessive and requested that current interest rates be used. Alfen *et al.* (2014) used the average return on federal loans with medium terms (8–12 years), which was 1.7 per cent in 2013 (the base year of the study), and forecasted this figure to increase to a value of 3.4 per cent in 2017. The difficulties of five-year forecasts for interest rates,⁸ and the problem of high fluctuations of running interest rates, are illustrated by Alfen *et al.* (2018). While the forecasted interest rate was 3.4 per cent for 2017 (Alfen *et al.*, 2014), the actual values in 2017 were 1.1 per cent for federal loans with 15–30-year terms (current rates) and 2.8 per cent when calculating a 12-year average⁹ for this type of loan. In order to tackle these difficulties, Alfen *et al.* (2018) used an average interest rate for outstanding federal loans with 10-year and 30-year terms, and applied this rate over the whole tolling period of 2018–22.

2.3 Running costs

Running costs — that is, operating costs such as lighting, traffic control, cleaning, grass cutting, snow sweeping, ongoing maintenance costs including minor repairs, and the cost of police and administration — make up a considerable share of total infrastructure costs. In the accounts for 2005–12, their share fluctuates between 22 per cent and 28 per cent, during the period 2013–17 even between 34 per cent and 45 per cent, and since 2018, this category amounts to 25 per cent of total infrastructure costs. Until 2012, running costs included capitalised renewal costs.

Disputes about the level of these costs is mainly driven by definition and classification issues, and by problems in statistical reporting. This paper will not further discuss issues arising in quantifying this cost, but gives a few examples of debatable quantities. One is

⁷Kotz *et al.* (1987) derived a range from 2 per cent to 3 per cent for the discount rate. The official CBA adopted the upper estimate as the official social discount rate.

⁸See Alfen *et al.* (2018, p. 34).

⁹On average, German federal loans are tied up for 12 years.

the inclusion of capitalised renewal costs during 2005–12, which amounted to between 0.25 €billion and 0.3 €billion p.a. Conceptually, these costs would be expected already to be included in depreciations. Another example of a definition issue is the inclusion of police costs, which has recently been questioned by the European Court (see decision from 28.10.2020, C-321/19). A further example is the inclusion of staff costs for personnel involved in issues around the federal roads at the transport ministry and the Infrastructure Financing Agency (VIFG) in the tolling study for 2018–22.

2.4 Cost allocation

The average cost principle requires allocating total costs — that is, also fixed, common, and joint costs to vehicle types. Since the methods used in particular for fixed, common, and joint costs often tend to distribute them more or less arbitrarily, the choice of an allocation procedure belongs to the most sensitive steps of infrastructure cost accounting. Link *et al.* (2008) show that the allocation approaches for road infrastructure costs in Europe, as well as overseas, vary considerably with respect to the required categorisation of costs including the related empirical base, and regarding allocation principles and factors applied to the respective cost categories. As Link *et al.* (1999) demonstrate, the choice of different allocation principles and factors lead to considerable variation of the cost share allocated to HGVs (ranging from 18 per cent to 48 per cent for Germany; 14 per cent to 43 per cent for Austria; and from 13 per cent to 36 per cent for Switzerland).

The official German road infrastructure cost accounts are based on a highly differentiated categorisation of costs. Costs are calculated for 16 different elements of infrastructure, each of them subdivided into costs for new construction and costs for renewals (except the costs for operation, police, and for operating the tolling system). Six different allocation principles are applied to these categories, aimed at meeting the principles of causality, asset specificity, and fairness (see Doll and Schaffer, 2007). These lead to distinctions between:

- proportionally (with respect to mileage) distributed costs (for example, common costs);
- weight-dependent costs of use (for example, wear and tear of the road surface);
- weight-dependent causation costs (for example, weight-dependent thickness of layers);
- capacity-dependent costs (width and geometry of roads);
- emission-dependent costs (for example, noise protection); and
- system-specific costs (for example, costs of the tolling system).

Different allocation factors are used for the total of 30 cost categories. Weight-dependent wear and tear costs for the road base, binder, and surface layers are allocated by weighting mileages with the AASTHO¹⁰ factors; the same is true for parts of the construction costs for the base and binder layers. Weight-dependent cost causation is accounted for by weighting the mileage either with the maximum permitted gross vehicle weight (applied for allocating capital costs of bridges) or with the AASHTO factors (applied for allocating

¹⁰The AASHTO factors express the damaging force of traffic loads on road pavement. They were derived from the data of the AASHO road test, a series of experimental studies that were designed as accelerated pavement tests and performed in the late 1960s in the USA. In these tests, variously loaded vehicles in different vehicle- and axle-combinations were driven on different types of road surfaces. The most important conclusion from this test was the so-called fourth power rule, which states that the damaging force is approximately proportional to the fourth power of its load (see Highway Research Board, 1961 for more details).

interest costs for the base and binder layer). Capacity-dependent costs are allocated by using equivalence factors (PCUs), which account for space requirements of different vehicle types with respect to length, width, speed, and safety distance of vehicles. Emission-dependent infrastructure costs (that is, the cost of noise protection infrastructure) are allocated by noise-equivalence figures.

The assignment of expenditures to the six allocation principles mentioned above is based on expert estimates, engineering-based arguments, and road construction norms (see, for example, Alfen *et al.*, 2014). The same is true for some of the allocation factors used. This, and the lack of accompanying research-oriented studies on crucial methodological elements of the calculations,¹¹ hampers to some degree the transparency and replicability of calculations. Overall, the share of infrastructure costs allocated to HGVs range from 44 per cent (Prognos and IWW, 2002; Progrtrans and IWW, 2007) to 46 per cent (Alfen *et al.*, 2014); since 2018, the cost share of tolled vehicles is 42 per cent, referring to the aggregate costs of motorways and federal roads. It should also be noted that the need to project mileages driven by different types of vehicles introduces some degree of uncertainty into the calculated charge level.¹²

2.5 Discussion

The weighted average charge, obtained from the calculations in the respective road cost accounts, has been subject to considerable fluctuations over time. Starting with a level of 15 € cents/vkm in 2005,¹³ it increased in the subsequent years to 18 € cents/vkm in 2012. Due to the methodological and empirical changes discussed in the previous sections, the charge declined sharply to 12 € cents in 2013, and increased to 13.7 € cents in 2017. For the tolling period 2018–22 the weighted average charge is 16 € cents, referring to the aggregate of motorways and federal roads, and therefore not comparable with the charge level before.

Summing up, although the calculation of HGV charges has been based on an established and agreed methodology since 2005, it involves various sensitive methodological and empirical choices that can lead — and have led — to considerable variance in results, as discussed in Sections 2.1 to 2.4. The calculation of average costs involves a complex methodology, which is empirically demanding to apply. This holds in particular for the choice of the synthetic method for capital valuation requiring an inventory of road assets and respective unit costs, and for the allocation procedure that requires the categorising of costs into around 30 different items. It is, therefore, far from being straightforward, easy, and transparent, as various claims of hauliers and haulier associations presented to the national and European court indicate.

3.0 Methods for Estimating Marginal Maintenance and Renewal Costs

During the last two decades, methodological and empirical foundations to estimate the single components of social marginal costs have made considerable progress, even

¹¹In contrast to the road cost accounting methodology in Switzerland, which is based on a set of frequently updated scientific base studies.

¹²There are deviations of up to 12 per cent between projected and real mileage in some years.

¹³This value and all other figures in this paragraph are at current prices.

though the availability of both estimation methodologies and quantitative outcomes varies between the components of social marginal costs and between modes of transport. Research on the pricing-relevant social marginal costs of road use has focused on studies of optimal congestion and environmental charges. Nevertheless, estimates on the marginal cost of operating, maintaining, and renewing roads, and experience in applying estimation methodologies, have also become available, which will be summarised in this section.

3.1 Estimation methods

Research in this field has developed along two methodological streams: cost function studies and duration studies. Cost function studies seek to estimate a functional relationship between the observed cost of operating, maintaining, and renewing infrastructure and traffic volume, road characteristics, and climate conditions.¹⁴ The duration approach uses physical measurements of road damages or road condition to estimate a functional relationship between these measurements, traffic volume, infrastructure characteristics, and climate as explanatory variables.

Cost-function analysis offers, meanwhile, a variety of tested and established functional forms, ranging from log-linear functions over Translog, Box-Cox, and hybrid forms. While cost-function studies for operating costs of roads (such as traffic signs, lighting, cleaning, snow sweeping, and grass cutting) are extremely rare (with Haraldsson, 2006 as a notable exception for Sweden¹⁵), there are various cost-function studies for maintenance as well as renewal costs. An empirical difficulty is to separate between expenditure for renewals and those for maintenance in the cost data, implying that some studies use a compound measure of both renewals and maintenance (for example, Bak and Borkowski, 2009). Most maintenance cost functions employ log-linear models partly as pooled cross-section studies (Schreyer *et al.*, 2002 for Swiss roads; Bak and Borkowski, 2009 for Polish roads), partly by accounting for the panel structure of data (Jonsson and Haraldsson, 2008). Link (2009) estimates and compares Cobb–Douglas, Translog, and Box-Cox model specifications for German motorways. Estimating joint models for passenger cars and trucks commonly faces multicollinearity problems. Indeed, only a few studies report separate estimates for these two types of traffic.

Deriving marginal renewal costs is challenging due to the lumpy nature of expenditures, and its dependence on both past and current traffic. The cost-function approach usually lacks cross-sectional cost data over a sufficiently long period and faces the problem of zero quantities in those years where no renewals were undertaken. Relatively simple approaches circumvent the problem by combining maintenance and renewal costs in a single measure of total costs (Bak and Borkowski, 2009), by using more geographically aggregated data (Wheat and Smith, 2008) or by cumulating renewal costs and traffic over time (Link, 2006). In addition, there are two more advanced approaches that aim to model the renewal process explicitly. The first is to apply corner solution models that are suitable for disaggregate data with a large proportion of zero values, an approach which

¹⁴In the absence of data on factor inputs and input prices on a cross-sectional level, the majority of econometric cost-function studies employ a single-equation approach and omit input prices, often arguing that prices are homogeneous across regions or responsible units.

¹⁵This study applies a log-linear single equation model with squared terms and random effects to data for Swedish roads, and reports a close to zero cost elasticity for this type of cost.

has so far only been applied for rail data (Andersson *et al.*, 2012). The second approach is duration modelling, which aims to establish the analysis of renewal costs on an engineering-based, theoretical understanding of the relationship between traffic load, infrastructure deterioration, and repair.

The first attempt to develop a comprehensive analytical model for marginal road renewal costs is Newbery (1985). This seminal paper derived the so-called fundamental theorem, which states that under several assumptions (such as a condition-responsive maintenance strategy,¹⁶ no damaging effect of weather, equal age distribution of the roads, and constant traffic flows), the marginal cost of pavement resurfacing equals the average resurfacing cost.¹⁷ However, accounting for weather effects reduces marginal costs below average costs. For example, the marginal cost is in a range of 75–90 per cent of average costs in dry climates and their share is even lower in more severe climates (Newbery, 1985). Traffic growth on low-volume roads reduces marginal cost further, while for high-volume roads the ratio between marginal costs and average costs increases.

Keeler and Small (1977) estimated marginal and average costs of road use, and derived optimal peak user tolls for the San Francisco Bay area within a model that integrates road construction and maintenance costs together with congestion costs. A modified model was applied in Starrs and Starkie (1986) for Southern Australia. Small *et al.* (1989) developed a comprehensive model on the social costs of road use for both congested and non-congested roads. Apart from marginal maintenance costs, they also calculated the optimal road durability (pavement thickness), which minimises the sum of capital costs and maintenance costs for given traffic loads expressed in ESALs.¹⁸ In contrast to Newbery (1985), they treat weathering as interacting with traffic load¹⁹ and derive marginal costs that are higher than average costs due to the weather effect. Lindberg (2002) introduces the concept of a deterioration elasticity that expresses the changed lifetime of a pavement induced by changes in traffic load. Based on a set of assumptions (no weathering effect, equal age distribution of roads, the deterministic and proportional relationship between road damage and traffic growth), Lindberg (2002) obtains the convenient result that the marginal cost of resurfacing an average road is a product of the average cost and the deterioration elasticity. Haraldsson (2007) and Nilsson *et al.* (2020) replace the assumption that road damage is deterministic and proportional to traffic load by a lifetime function that is estimated by a survival model. A recent application of this approach for Germany is Murray and Link (2020). It should be noted that all of these studies deal exclusively with the cost of resurfacing, except in Small *et al.* (1989), where resurfacing cost and thickness of the road base are jointly considered. So far, no application for engineering constructions such as bridges

¹⁶In a condition-responsive maintenance strategy, the road authority responds to road damages by resurfacing any particular road when it reaches a predetermined trigger value of roughness.

¹⁷Furthermore, the extra vehicle operating cost imposed on other vehicles are negligibly small. Such road damage externality is caused when a vehicle damages the road surface and increases its roughness, and thereby increases the vehicle operating cost of subsequent vehicles.

¹⁸The concept of ESALs (Equivalent Single Axle Load) was developed from data collected within the AASHTO road test in order to establish a damage relationship for comparing the effects of axles carrying different loads. The reference value is 18,000 lb (80 kN) for a single axle with dual tyres in the USA and the UK; some countries use a 100 kN value (Norway, Sweden). German road design norms use a standardised 10 t standard axle (FGSV, 2015).

¹⁹However, they assume no such effect for rigid pavements.

has been available. Therefore, marginal renewal costs should be interpreted as a lower bound referring only to parts of roads.

3.2 Quantitative evidence on marginal costs

A review of international marginal cost studies for roads (see Link, 2015) arrives at some general patterns, even though different methodological approaches, the scope of analysis (type of road network, disaggregation of traffic variables), and uncertainties on the definition of maintenance costs as opposed to renewals have to be taken into account. While a comparison of estimated marginal costs is not sensible due to differences in wage levels, material costs, and so on, the cost elasticity as the ratio between marginal and average costs is a useful indicator for comparisons of different national results. Most studies obtain a falling elasticity curve and the cost elasticity is higher as the time-horizon of the infrastructure measure (that is, operation, ongoing maintenance, renewals) increases. While the cost elasticity for operation appears to be close to zero, it ranges from 0.3 to 0.58 for maintenance work (with lower figures in those models that consider trucks and passenger cars jointly in the models). For renewals, Lindberg (2002) obtains a cost elasticity of 0.36, but Nilsson *et al.* (2020) find only a value of 0.08 (both referring to Sweden). For Germany, there is evidence that the cost elasticity of HGVs for ongoing maintenance ranges between 0.14 and 0.17, while results from two different methodological approaches to estimate marginal renewal costs show a larger bandwidth, between 0.39 and 0.82 (Table 5). Overall, the results for marginal maintenance costs are at the lower bound, those for renewal costs rather in the middle or even upper bound of available international estimates.

Using these results for HGV charging would require differentiating them further into weight classes and/or axle configurations. This could be performed either by using the AASHTO factors, or — if studies are based on ESALs — by converting the observed ESALs into mileage driven by vehicles in different vehicle and axle configurations.

Table 5
Cost Elasticities of Road Freight Vehicles with Respect to Traffic in Germany

<i>Study</i>	<i>Type of roads</i>	<i>Type of data</i>	<i>Functional form</i>	<i>Cost elasticity¹</i>
<i>Maintenance</i>				
Link (2009)	Motorways	Pooled cross-section, 2005–6	Box-Cox single equation model	0.17
Link (2014)	Federal roads (Bundesstraßen) ²	Pooled cross-section, 2005–7	Hybrid multi-equation model with factor inputs and input prices	0.14
<i>Renewals</i>				
Link (2006)	Motorways ³	Panel, 1980–99	Translog multi-equation model with factor inputs and input prices. Between estimator	0.82
Murray and Link (2020)	Motorways ³	Panel, 1980–2015	Duration model, estimated as accelerated failure time Weibull model	0.39

¹ Weighted average cost elasticity. ² Refers to West Germany. ³ Refers to the state of Hesse.

3.3 Discussion

Estimating marginal road infrastructure costs indeed involves complexity in econometric methods and requires suitably disaggregated data, preferably on a cross-sectional level over a sufficiently long time — that is, panel data. With respect to econometric estimation methods, it can be concluded that there has been considerable progress in testing different methods; and the range of estimates is getting closer, in particular when focusing on a set of studies for one country. Established cost-function techniques, such as the Translog cost function, are meanwhile workhorses that are successfully applied for regulating rail track access charges in various countries. This, and the fact that the empirical base has improved too, not least fostered through the data requirements for the average cost studies for calculating HGV charges, lead to the conclusion that marginal costs can serve as a basis for charge setting in road freight transport.

Nevertheless, open methodological issues remain, which require attention from researchers to make marginal cost estimations a suitable base for charging. The main issue in this context is the need to differentiate estimates by types of vehicles.

4.0 Impacts of Average Cost-based HGV Charging

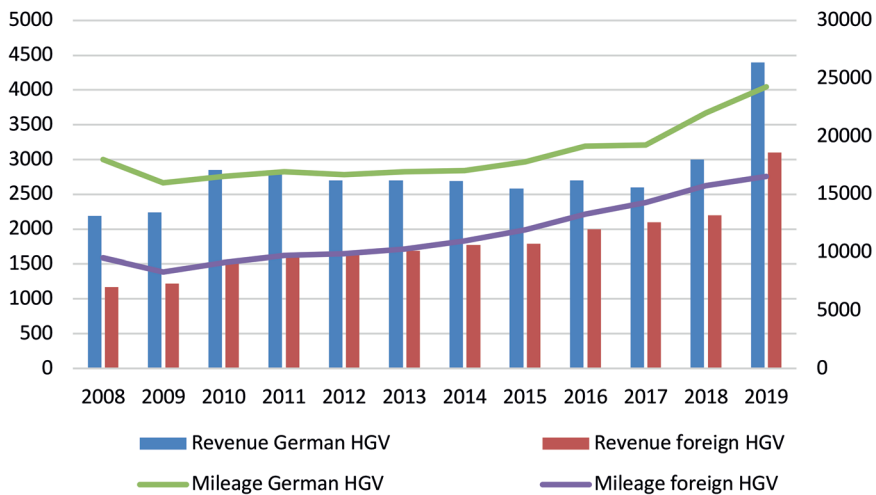
While economic theory prefers marginal cost-based charges over average cost-based ones, the question remains how the observed impacts of the average cost-based German HGV charging scheme would compare with a (hypothetical) marginal cost-based scheme.

Starting with the goals that the implemented HGV charging scheme was intended to achieve, it was foremost to initiate a shift from public budget funding towards the user pays principle, and to make foreign HGVs using German motorways contribute to the costs they cause. Often mentioned in the political debate as further goals were to achieve a modal shift to more environmentally friendly modes (such as rail and inland waterways), and to strengthen innovative technologies such as the tolling system. The scheme was successful in generating revenues (Figure 1), which amounted to around €7.1 billion in 2019, providing funds that have been spent to finance road, rail, and inland waterway infrastructure.²⁰ The scheme was also successful in achieving financial contributions from foreign HGVs. Their share in total mileage of tolled vehicles has increased from around half in 2007 to almost three-quarters in 2017; their share in toll revenues made up around one-third at the beginning of charging and has increased to 45 per cent in 2018. However, HGV charging did not lead to a decrease in road use (as the increase of mileage indicates²¹), indicating a rather low price elasticity. The impacts on modal shift are less clear. During the period 2004–18, rail freight tonne-km has grown faster than both total and road freight tonne-km in most years. However, the modal shares of both rail and road freight transport have increased at the expense of the share of inland waterway

²⁰From 2010 onwards, revenues are solely used for road funding; however, public budget funds for roads were decreased by the amount to which toll revenues were originally spent for rail and inland waterways.

²¹Mileage of tolled vehicles has experienced a considerable annual growth, not least due to the extension of the scheme. Annual growth rates were between 2.4 per cent and 12.4 per cent, with a decline in 2007–9 due to the global financial crisis and a decline in 2012. Detouring of trips to non-tolled parts of the road network has played only a marginal role (see Deutscher Bundestag, 2006, 2014).

Figure 1
Toll Revenues (Mill. €, Left Vertical Axis) and Mileages (Mill. Vehicle-km, Right Vertical Axis)
from German and Foreign HGVs in Germany

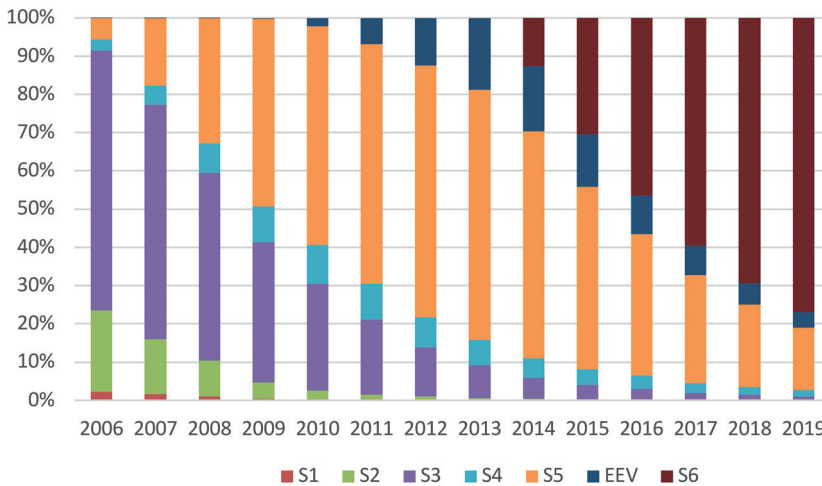


Source: BAG Annual Reports, several years. Accessible at: www.bag.bund.de/DE/Navigation/Verkehrsaufgaben/Marktbeobachtung/Herbst_und_Jahresberichte/herbst_und_jahresberichte_node.html.

transport. The positive trend of rail freight can thus not be attributed directly to HGV tolling, but is also a result of a set of economic framework conditions such as high fuel costs, combined with shortage of load capacity in road freight. Probably the most significant effect of the tolling scheme is the shift of mileage to trucks with higher environmental standards (Figure 2), even though this effect has also been driven by the availability of cleaner technologies and the introduction of the respective technology standards in the EU. From 2006 to 2012, the share of Euro 5 vehicles in total mileage has grown from 6 per cent to 66 per cent, and has since then declined in favour of Euro 6 vehicles, which made up more than three-quarters of mileage in 2019.

Given the overall positive outcomes of the average cost-based pricing of HGVs in Germany, the provocative question arises why to move towards a marginal cost-based scheme at all, and if so, which impacts can be expected. While calculating a differentiated social marginal cost-based scheme for HGVs is not the subject of this paper, it is nevertheless possible to indicate how such a scheme would deviate from the current one. Apparently, from the perspective of marginal cost, the current scheme implies an overcharging for the cost of operation, maintenance, and renewals, but an undercharging for air pollution costs (considering NO_x, PMs, SO₂, NMVOC, and NH₃) due to the maximum percentage of charge variation requested by the EU directives. Therefore, the infrastructure part of the HGV charge would be considerably lower, although potentially more differentiated by weight and axle combinations. This would be accompanied by an increase of the air pollution charge, where currently, for 2018–20, only between 76 per cent and 94 per cent of costs can be charged (see Alfen *et al.*, 2018). Furthermore, the noise charge, which currently covers only 45 per cent of calculated noise costs and is charged as a uniform amount to all HGVs, would be higher and vary between day and night-time. Leaving

Figure 2
Mileage Distribution of Tolloed Vehicles by Emission Exhaust Class



Source: BAG Annual Reports, several years. Accessible at: www.bag.bund.de/DE/Navigation/Verkehrsaufgaben/Marktbeobachtung/Herbst_und_Jahresberichte/herbst_und_jahresberichte_node.html.

aside the discussion whether CO₂ should be priced by a charge for road use or by fuel taxes and/or emission trading, a social marginal cost pricing scheme would include a congestion charging element. This, however, is only sensible when all vehicles including passenger cars are subject to road user charging, therefore remaining a future task. Furthermore and importantly, a move towards a social marginal cost scheme would require the EU to amend the charging directive.

Apart from the presumed calculation complexity, the major argument against marginal cost pricing is the failure to recover costs. This is true for the infrastructure part of such a scheme: the available evidence from marginal infrastructure cost studies indicates that between 14 per cent and 17 per cent of maintenance costs, and around 40 per cent of renewal costs, can be recovered when charging marginal costs, while operating expenditures and administration costs would not be recovered at all. Without any access to the allocation procedure and the underlying empirical base used for calculating the current average charge, it is not possible to quantify the resulting overall deficit. However, a social marginal cost scheme that charges for air pollution, noise, and congestion has the potential to compensate for the lower infrastructure charge, and would send price signals for an efficient use of fuels and scarce road capacity.

5.0 Conclusions

This paper has focused on the complexity in calculating average costs and marginal costs of road infrastructure (that is, the costs of operating, maintaining, and renewing roads) as a basis for German HGV charging. The analysis has shown that calculating average cost-based charges is far from being straightforward, easy, and transparent, even with an agreed methodology as in Germany. The data requirements to apply this methodology

are huge, and various sensitive choices both in the methodology and in some of the parameters can lead to considerable variations in results and charges, giving rise to claims of road users against the national and the European Court (see BGL, 2018; and for a recent example European Court, 2020). The review of methods and the bandwidth of estimates from marginal cost estimation has shown that research in this field has made considerable progress. In addition, the availability of data for marginal cost estimation has improved, because the average cost calculations performed in Germany have also required more disaggregated data. This leads to the conclusion that the argument of too high complexity in estimating marginal costs, and the resulting preference for a presumed simpler and more transparent calculation of average costs, does not hold. The use of marginal cost estimates in regulating rail track access charges underlines this.

Beside the complexity of calculation argument, the question remains whether the current average cost-based scheme performs so badly that a move towards a marginal cost-based scheme would be an urgent step. Germany applies a charging scheme that is differentiated by relevant drivers of marginal infrastructure costs such as weight classes, axle configurations, and emission classes. Only the Austrian and the Swiss schemes have a similar or even higher degree of differentiation, while most countries raise less differentiated charges²² or even still apply time-based schemes (UK, the Netherlands, Luxemburg, Denmark, and Sweden).

While the positive outcomes of the current scheme such as provision of revenue and the shift towards the use of more environmentally friendly vehicles do not indicate an urgent need, this paper raises a plea in favour of a social marginal cost scheme. A restructuring of the charge by reducing and further differentiating the infrastructure charge, increasing and differentiating air pollution and noise charges, and, in particular, introducing a congestion charge, will foster the capability of road user charging to provide for an efficient use of resources and road capacity, and to reflect as closely as possible road damage.

References

- Alfen, Aviso, and BUNG (2018): *Berechnung der Wegekosten für das Bundesfernstraßennetz sowie der externen Kosten nach Maßgabe der Richtlinie 1999/62/EG für die Jahre 2018–2022*. Gutachten im Auftrage des Bundesministeriums für Verkehr und digitale Infrastruktur, Weimar, Leipzig, Aachen, Münster, Köln.
- Alfen, Aviso, and IVM (2014): *Berechnung der Wegekosten für das Bundesfernstraßennetz sowie der externen Kosten nach Maßgabe der Richtlinie 1999/62/EG für die Jahre 2013–2017*. Gutachten im Auftrage des Bundesministeriums für Verkehr und digitale Infrastruktur, Weimar, Leipzig, Aachen, Münster.
- Andersson, M., A. S. J. Smith, A. Wikberg and P. Wheat (2012): 'Estimating the marginal cost of railway track renewals using corner solution models', *Transportation Research Part A*, 46, 954–64.
- Arrow, K. J., W. R. Cline, K. G. Maler, M. Munasinghe, R. Squitieri, and J. E. Stiglitz (1996): 'Intertemporal equity, discounting, and economic efficiency', in J. P. Bruce, H. Lee, and E. F. Haites (eds), *Climate Change 1995 — Economic and Social Dimensions of Climate Change*, Cambridge, UK, New York and Melbourne: Cambridge University Press, Chapter 4, pp. 125–44.

²²For example, the toll schemes in Italy, France, and Poland have two weight classes for trucks, while Belgium sets different charges for three weight classes of trucks. The schemes in the Czech Republic and Hungary include three classes of axle configurations, the Slovakian one even four-axle classes. Most countries differentiate further by the emission class of the vehicle.

- Bak, M. and P. Borkowski (2009): *Marginal Cost of Road Maintenance and Renewal in Poland*. Annex 2 to CATRIN (Cost Allocation of Transport Infrastructure cost) Deliverable D6 Road Cost Allocation for Europe: Recommendations and open questions. Funded by the Sixth Framework Programme. VTI, Stockholm.
- Bayliss, B. T. and A. I. Millington (1995): 'Deregulation and logistics systems in a Single European Market', *Journal of Transport Economics and Policy*, 29(3), 305–316.
- Baumol, W. J. (1968): 'On the social rate of discount', *The American Economic Review*, 58, 788–802.
- Baumol, W. J. (1969): 'On the social rate of discount: comment on the comments', *American Economic Review*, 59, 930–930.
- Beckers, T., J. P. Klatt, G. Corneo, and H. Mühlenkamp (2009): *Zeitliche Homogenisierung und Berücksichtigung von Risiko im Rahmen von Wirtschaftlichkeitsuntersuchungen*. Gutachten im Auftrag des Bundesrechnungshofes, Berlin, Speyer.
- BGL (2018): Press Release from 19 June 2018 on the claim regarding toll calculation and its withdrawal. www.bgl-ev.de/web/medien/presse/article_archiv.htm&news=3286&year=2018 (accessed 10 December 2020).
- Boadway, R. (2006): 'Principles of cost-benefit analysis', *Public Policy Review*, 2, 1–44.
- Brenner, A. (1997): 'Wegerechnungen für das Schienennetz', *Giessener Studien zur Transportwirtschaft und Kommunikation*, Band 12.
- CEC (1995): 'Towards Fair and Efficient Pricing in Transport. Policy Options for Internalising the External Costs of Transport in the European Union' EU Green Paper. COM (95) 691 Final, 20 December, Brussels.
- CEC (1998): 'Fair payment for infrastructure use: a phased approach to a common transport infrastructure charging framework in the EU', EU White Paper. COM (98) 466 final, 22 July.
- CEC (2001): 'European transport policy for 2010: time to decide', EU White Paper. COM (2001) 370 final, 12 September, Brussels.
- Clark, J. M. (1923): *Studies in the Economics of Overhead Costs*, University of Chicago Press, Chicago, IL.
- Cline, W. R. (1999): 'Discounting for the very long term', in P. R. Portney and J. P. Weyant (eds), *Discounting and Intergenerational Equity*, Routledge, London, pp. 131–40.
- Coase, R. H. (1946): 'The marginal cost controversy', *Economica*, 13, 169–82.
- Deutscher Bundestag (2006): *Bericht über Verkehrsverlagerungen auf das nachgeordnete Straßennetz infolge der Einführung der Lkw-Maut*. Drucksache 17/12028. <http://dip21.bundestag.de/dip21/btd/17/120/1712028.pdf> (accessed 16 November 2020).
- Deutscher Bundestag (2014): *Bericht über Verkehrsverlagerungen auf das nachgeordnete Straßennetz infolge der Einführung der Lkw-Maut auf vier- und mehrstreifigen Bundesstraßen*. Drucksache 18/689. <http://dipbt.bundestag.de/dip21/btd/18/006/1800689.pdf> (accessed 16 November 2020).
- Doll, C. and A. Schaffer (2007): 'Economic impact of the introduction of the German HGV toll system', *Transport Policy*, 14, 49–58.
- European Court (2020): Reference for a preliminary ruling — Directive 1999/62/EC — Directive 2006/38/EC — Charging of heavy goods vehicles for the use of certain infrastructures — Article 7(9) — Article 7a(1) and (2), Case C-321/19. <https://eur-lex.europa.eu/legal-content/EN/TEXT/HTML/?uri=CELEX:62019CJ0321&from=DE> (accessed 10 December 2020).
- FGSV (2015): *Guidelines for the Standardization of Pavement Structures of Traffic Areas — RstO 12*. Cologne. www.fgsv-verlag.de/pub/media/pdf/499_E_PDF.v.pdf (accessed 7 December 2020).
- Groom, B. and D. Maddison (2013): *Non-identical Quadruplets: Four New Estimates of the Elasticity of Marginal Utility for the UK*, Grantham Research Institute on Climate Change and the Environment, London.
- Haraldsson, M. (2006): *Marginal Cost for Road Maintenance and Operation — a Cost Function Approach*. Annex 1.2BI to Deliverable D3, Marginal cost case studies. GRACE (Generalisation of Research on Accounts and Cost Estimation). EU-Project funded by Sixth Framework Programme. ITS, University of Leeds, Leeds.
- Haraldsson, Mattias (2007): *The Marginal Cost for Pavement Renewal: A Duration Analysis Approach*, Statens väg-och transportforskningsinstitut.
- Harberger, A. C. (1972): 'On measuring the social opportunity cost of public funds', in Harberger, A. C. (ed.) *Project Evaluation: Collected Papers*, Macmillan Press, London and Basingstoke, 94–112.

- Highway Research Board (1961): *The AASHO-Road-Test — History and Description of Project*. Special Report 61 A, Washington, DC.
- Holocher, K. H. (1998): 'Wegerechnungen für Straßen', in *Giessener Studien zur Transportwirtschaft und Kommunikation*, Band 3.
- Keeler, T. E. and K. A. Small (1977): 'Optimal peak-load pricing, investment, and service levels on urban expressways', *Journal of Political Economy*, 85, 1–25.
- Koopmans, T. C. (1965): 'On the concept of optimal economic growth', in *The Economic Approach to Development Planning*, Pontificae Academiæ Scientiarum Scripta Varia, 28, pp. 225–300.
- Kotz, R., P. Müller, and W. Rothengatter (1987): *Entwicklung eines Verfahrens für dynamische Investitionsplanung und Ermittlung des bei der Fortschreibung der BVWP anzuwendenden Zinssatzes*, Gutachten im Auftrage des Bundesministeriums für Verkehr, Universität Ulm.
- Lindberg, G. (2002): *Marginal Costs of Road Maintenance for Heavy Goods Vehicles on Swedish Roads*, Annex A2 of Deliverable 10 of the UNITE project, Linköping.
- Link, H. (2006): 'An econometric analysis of motorway renewal costs in Germany', *Transportation Research Part A*, 40, 19–34.
- Link, H. (2009): *Marginal Costs of Road Maintenance in Germany*, Annex 3 to Deliverable D6, Road Cost Allocation for Europe: Recommendations and open questions, CATRIN (Cost Allocation of Transport Infrastructure), EU-Project funded by Sixth Framework Programme. VTI, Stockholm.
- Link, H. (2014): 'A cost function approach for measuring the marginal cost of road maintenance', *Journal of Transport Economics and Policy*, 48, 15–33.
- Link, H. (2015): 'Road and rail infrastructure costs', in C. Nash (ed.), *Handbook of Research Methods and Applications in Transport Economics and Policy*, Edward Elgar Publishing, Cheltenham.
- Link, H., J. S. Dodgson, M. Maibach, and M. Herry (1999): *The Costs of Road Infrastructure and Congestion in Europe*, Physica/Springer Heidelberg-New York.
- Link, H., A. Stuhlemmer, M. Haraldsson, P. Abrantes, P. Wheat, S. Iwnicki, C. Nash, and A. Smith (2008): *Cost Allocation Practices in the European Transport Sector*, Deliverable D1, CATRIN (Cost Allocation of Transport Infrastructure cost), Funded by Sixth Framework Programme. VTI, Stockholm, March.
- Link, H., D. Kalinowska, U. Kunert, and S. Radke (2009): *Wegekosten und Wegekosten-deckung des Straßen- und Schienenverkehrs in Deutschland im Jahre 2007*, Politikberatung kompakt 53.
- Murray, N. and H. Link (2020): 'A duration approach for estimating the marginal renewal cost at German motorways', DIW Discussion Papers No. 1898.
- Nash, C. (2003): 'Marginal cost and other pricing principles for user charging in transport: a comment', *Transport Policy*, 10, 345–8.
- Newbery, D. M. (1985): 'The fundamental theorem of road user charges', No. 59. CEPR Discussion Papers.
- Nilsson, J. E., K. Svensson, and M. Haraldsson (2020): 'Estimating the marginal costs of road wear', *Transportation Research Part A: Policy and Practice*, 139, 455–71.
- Prognos and IWW (2002): *Wegekostenrechnung für das Bundesfernstraßennetz unter Berücksichtigung der Vorbereitung einer streckenbezogenen Autobahnnutzungsgebühr*. FE-Nr. 96.693/2001, Bundesministerium für Verkehr, Bau- und Wohnungswesen, Berlin.
- Prograns and IWW (2007): *Aktualisierung der Wegekostenrechnung für die Bundesfernstraßen in Deutschland*. Gutachten im Auftrage des Bundesministeriums für Verkehr, Bau und Stadtentwicklung, Berlin.
- Ramsey, F. P. (1928): 'A mathematical theory of saving', *Economic Journal*, 38, 548–59.
- Rothengatter, W. (2003): 'How good is first best? Marginal cost and other pricing principles for user charging in transport', *Transport Policy*, 10, 121–30.
- Rothengatter, W. (2018): 'Mr. Dupuit and the marginalists', *Transport Policy*, 70, 32–9.
- Schreyer, C., N. Schmidt, and M. Maibach (2002): *Road econometrics – Case study motorways Switzerland*, UNITE (UNification of accounts and marginal costs for Transport Efficiency) Deliverable 10, Annex A1b. Funded by EU 5th Framework RTD Programme. ITS, University of Leeds, Leeds. <http://www.its.leeds.ac.uk/projects/unite/> (accessed 7 December 2020).
- Small, K. A., C. C. Winston, and C. A. Evans (1989): *Road Work: A New Highway Pricing and Investment Policy*, The Brookings Institution, Washington.
- Solow, R. (1974): 'The economics of resources or the resources of economics', *American Economic Review Papers and Proceedings*, 64, 1–14.

- Starrs, M. M. and D. N. Starkie (1986): 'An integrated road pricing and investment model: a South Australian application', *Australian Road Research*, 16, 1–9.
- Stern, N. H., S. Peters, V. Bakhshi, A. Bowen, C. Cameron, S. Catovsky, and D. Zenghelis (2006). *Stern Review: The economics of climate change* (Vol. 30). Cambridge: Cambridge University Press. https://webarchive.nationalarchives.gov.uk/20100407172811/http://www.hm-treasury.gov.uk/stern_review_report.htm (accessed 7 December 2020).
- UN (2020): Perpetual Inventory Method — SNA. Statistics Glossary. Available at <https://unstats.un.org/unsd/nationalaccount/glossresults.asp?gID=436> (accessed 7 December 2020).
- Wheat, P. and A. Smith (2008): 'Assessing the Marginal Infrastructure Maintenance Wear and Tear Costs for Britain's Railway Network', *Journal of Transport Economics and Policy*, 42(2), 189–224.