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CATRIN

Cost Allocation of TRansport INfrastructure cost

Deliverable D1

Cost allocation Practices in the European Transport Sector

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Abbreviations

AADT	Annual average daily traffic
AASH(T)O road test	Road test carried out by the American Association of State Highway and Transportation Officials
AC	Average costs
AGM	Average gross mass
ATM	Air traffic movements
CoA	Coefficient Agressivite
DLC	Dynamic load coefficient
ESAL	Equivalent single axle load
EGTM	Equivalent gross tonne mile
EVM	Equivalent vehicle mile
FAA	Federal Aviation Authority
FAC	Fully allocated costs
FHA	Federal Highway Administration
GTM	Gross tonne mile
HGV	Heavy goods vehicles (goods vehicles with a maximum GVW equal or more than 3.5 tonnes)
LGV	Light goods vehicles (goods vehicles with a maximum GVW less than 3.5 tonnes)
MC	Marginal costs
ORR	Office of the rail regulator
PCU	Passenger car unit
USM	Unsprung mass
Vkm	vehicle km
WLU	Work load units (1 WLU equals to 1 passenger incl. baggage or 100kg air freight)

0 Executive Summary

The CATRIN project aims to support policy makers in implementing efficient pricing strategies in all modes of transport, e.g. pricing strategies which arte based on the social marginal cost principle. Specifically, it addresses the allocation of infrastructure costs in all modes of transport. The motivation to conduct a research project on this issue is the fact that available studies on marginal infrastructure costs tend to provide some type of “average” marginal cost estimates but often fail to obtain marginal cost estimates by types of vehicles or groups of users. On the other hand, a range of fully allocated cost studies are available which provide average cost estimates by type of vehicle. However, using these studies for pricing purposes bears problems. Average costs are not the appropriate basis for efficient pricing, and the allocation methods used in these studies often tend to allocate arbitrarily fixed, common and joint costs to vehicle types. As a consequence, average costs by vehicle types vary greatly, depending on the methodology used.

This deliverable D1, Cost Allocation practices in the European Transport Sector, is one of two reports from WP1 – State of the art methodology and survey of existing practice. It summarises the existing practice of cost estimation and cost allocation in all modes of transport. Its purpose is to identify gaps and open issues in allocation methods which currently prevent the use of marginal cost figures in pricing, and to analyse the methodological background of available studies. As the whole CATRIN project, the focus is on infrastructure costs, e.g. on the costs of providing, maintaining, renewing and operating infrastructure. The second deliverable from WP1 provides the internal blueprint for the case studies to be conducted in CATRIN.

As far as available within each mode, two types of studies are analysed: First, genuine marginal cost studies either based on econometric methods or on engineering approaches. The focus in analysing marginal cost studies is rather on the type of results obtained than on figures. Second, fully allocated cost studies. The main interest is here whether the underlying allocation methods are based on coherent assumptions within each country and supported by appropriate databases, as well as to analyse whether assumptions differ across countries.

The analysis of available research shows a varying picture across modes. Marginal cost studies have emerged over the recent years within EU funded projects, in particular for road and rail. Fully allocated cost studies exist traditionally in the road sector where a considerable body of estimation and allocation methods is available, and though to a lesser extent in the rail sector and in aviation. The situation is rather poor in waterborne transport.

The review of available research on estimating marginal infrastructure costs and the analysis of methodologies used and quantitative results obtained has revealed a specific problem encountered in all studies. This problem relates to the need of any quantitative studies to have access to comprehensive databases which allow to extract the necessary information in the required level of disaggregation and to apply advanced estimation techniques. However, across modes data availability on the cost of maintaining, operating and renewing transport infrastructure as well as on the use of infrastructure is poor. Most projects in this line of research therefore have to allocate much resources to compile data in a form which allows to draw any conclusions of policy relevance. It is therefore noteworthy that some common conclusions have been emerging from cost studies in different countries.

From the review of national practice and available research we have gained the following insights:

- Bearing the difficulties in obtaining and compiling appropriate databases in mind and given the fact that estimating marginal infrastructure costs has been a relatively young field of research, it can be concluded that research on estimating marginal infrastructure costs has made remarkable progress in understanding marginal costs in different modes. Nevertheless, there remain outstanding issues to be solved.
- One of the most important policy-relevant findings from marginal cost studies is evidence on the degree of cost variability and on the cost elasticity, e.g. the ratio between MC and AC. For both road and rail, the studies provide evidence that the mean value of the cost elasticity is generally below 1 (road) and 0.5 (rail) respectively. Furthermore, the cost elasticity increases with the time horizon of the measure (for example for road operation: close to zero, for road maintenance: 0.12-0.69, for road renewals: 0.57-0.87, for rail maintenance: 0.07-0.26, for rail maintenance and renewals: 0.18-0.302). Across studies, the variation of the cost elasticity is larger for studies which deal with maintenance costs

than for those dealing with other types of infrastructure measures which might hint at problems with defining and quantifying maintenance expenditures.

- At the current frontier of research, marginal cost studies have not yet achieved convergence regarding the shape of the MC curve (decreasing versus increasing). This holds in particular true for the road sector, to some extent also for rail. It appears that for rail the most consistent finding from econometric studies is that i) marginal costs fall with traffic levels, and, ii) are initially very high with low usage levels but fall then sharply. This finding is in contrast to the engineering expectation of a proportional increase of wear & tear with usage.
- For all modes available marginal cost studies obtain “average” marginal cost estimates but fail to provide estimates which are disaggregated by vehicle types or user groups. The MC results are therefore currently not yet in the form needed for pricing policy.
- In air transport, the majority of studies suggest increasing returns to scale of airport maintenance and operation which implies a decreasing marginal cost. Similar to rail, non-linearities are strong for a lower range of usage and rather weak for higher output values. The comparability of results is restricted by the use of different output measures (air transport movements, passenger numbers, work load units) in the studies. Similar to road and rail marginal cost estimates per aircraft type are lacking so far.
- Fully allocated cost studies play a major role in for the road sector. The analysis of allocation procedures used in these studies has shown that there is a considerable variation in the methodologies and allocation factors. Almost all studies split total costs either into fixed and variable costs or into weight-dependent and non-weight dependent costs, an information which can be used as proxy for marginal cost and, in case of weight-dependent costs, as a starting point for allocating marginal costs to vehicle types.
- Further information from fully allocated cost studies are the allocation factors used. The most important factors are the ASSH(T)O factors for allocating weight dependent costs and PCU figures for allocating other types of costs other parts of variable costs but also fixed costs if such an allocation is necessary to meet a budget constraint). The review has shown that, while in principle the definition and calculation of the ASSH(T)O is straightforward, country-specific differences arise from the different disaggregation of mileage data by vehicle weight classes, the measurements of vehicle loadings, from the

distribution of total weight to the axles and from a different reflection of the fact that axle configurations such as tandem or triple axles cause higher road damages than single axles.

- In contrast to the AASH(T)O factors, PCU figures vary between countries not only to different disaggregations of vehicle mileage data in transport statistics but also due to methodological differences. Depending on the underlying concept, PCUs are based on average speed, traffic density, average distance between vehicles within the traffic flow, safety distances and delays. The impact of heavier vehicles on traffic flow is considered by vehicle characteristics such as length and the ratio between weight and engine power on the one hand, and the existence and length of gradients, the share of trucks in the traffic flow, the number of lanes and traffic density on the other hand.

1 Introduction

The CATRIN project aims to support policy makers in implementing efficient pricing strategies in all modes of transport, e.g. pricing strategies which are based on the social marginal cost principle. Specifically, it addresses the allocation of infrastructure costs in all modes of transport. The motivation to conduct a research project on this issue is the fact that available studies on marginal infrastructure costs tend to provide some type of "average" marginal cost estimates but often fail to obtain marginal cost estimates by types of vehicles or groups of users. On the other hand, a range of fully allocated cost studies are available which provide average cost estimates by type of vehicle. However, using these studies for pricing purposes bears problems. Average costs are not the appropriate basis for efficient pricing, and the allocation methods used in these studies often tend to allocate arbitrarily fixed, common and joint costs to vehicle types. As a consequence, average costs by vehicle types vary greatly, depending on the methodology used.

This deliverable D1, Cost Allocation practices in the European Transport Sector, is one of two reports from WP1 – State of the art methodology and survey of existing practice. It summarises the existing practice of cost estimation and cost allocation in all modes of transport. Its purpose is to identify gaps and open issues in allocation methods which currently prevent the use of marginal cost figures in pricing, and to analyse the methodological background of available studies. As the whole CATRIN project, the focus is on infrastructure costs, e.g. on the costs of providing, maintaining, renewing and operating infrastructure. Obviously, there exists a close relationship between scarcity and congestion costs and infrastructure. This relationship is dealt with in deliverable D3 of CATRIN and will not be discussed in detail here. The second deliverable from WP1 provides the internal blueprint for the case studies to be conducted in CATRIN.

This document is organised a s follows. Chapter 2-5 summarises the review of existing studies for road, rail, air transport and waterborne transport. As far as available within each mode, two types of studies are analysed: First, genuine marginal cost studies either based on econometric methods or on engineering approaches. The focus in analysing marginal cost studies is rather on the type of results obtained than on figures. Second, fully allocated cost studies. The main interest is here whether the underlying allocation methods are based on coherent assumptions within each country and supported by appropriate databases, as well as to analyse whether assumptions differ across countries. Chapter 6 concludes.

2 State of the art – Studies on road infrastructure costs

The available research analysed in this report falls into two groups of studies. First, genuine marginal cost studies which are either based on observed spending for roads and apply neoclassical production and cost function theory on this type of data, or studies which use engineering-based information on road damage, optimal road design and optimal pavement maintenance and renewal cycles for estimating marginal costs. Second, fully allocated cost studies where total road infrastructure costs are estimated for specific cost categories and allocated to vehicle categories by using allocation factors.

2.1 Marginal cost studies

Over the recent years a number of marginal cost studies dealing with maintenance and renewal costs of roads have been performed, mainly within the European research projects UNITE and GRACE. Two general approaches can be distinguished.

First, econometric studies which estimate a functional relationship between the cost of infrastructure operation, maintenance and renewal, and the traffic volume, factor input prices for infrastructure measures, road characteristics and climate. The relationship identified between cost and traffic volume serves then as the basis for deriving marginal costs of infrastructure use. Econometric cost function analysis uses observed, real expenditures for infrastructure maintenance, repair and operation and observations of (potential) cost drivers, either based on cross-sectional or longitudinal data. Second, so-called duration approaches which use (physical) measurements of road damages or measurements of road condition to estimate a relationship between these measurements, traffic volume and other explanatory variables. The obtained damage-traffic relationships are evaluated in monetary terms by using unit costs for road work. These approaches refer exclusively to renewal costs. A lifetime or duration function is estimated as a function of infrastructure characteristics, geographical and climate information and the traffic utilisation as in the econometric approach. The change in the lifetime as a consequence of traffic change affects the present value of future renewal costs and is thus the base for the marginal cost calculation. In the following, we analyse the available studies under three aspects:

- Do these studies provide marginal cost estimates for different types of vehicles?
- Can a general pattern for the shape of the marginal cost curve be concluded?

- What are the open issues arising from available marginal cost studies?

2.1.1 Econometric cost function studies

The available studies differ regarding the type of road measure anaylsed (operation: 2 studies, maintenance: 4 studies, renewals: 4 studies, sum of maintenance and renewals: 1 study), the type of road (motorways, national roads, all roads) as well as regarding the methodological approach (table 1).

The majority of econometric cost function studies for road infrastructure are based on single-equation models. In these models factor inputs and input prices are neglected, mainly due to lack of the necessary cross-sectional data[1]. The functional form used is either a log-linear specification (Sedlacek et al. 2002, Schreyer et al. 2002, Bak et al. 2006, Haraldsson 2007) or a translog-model (Link 2002 and 2006, Haraldsson 2006a). Costs are explained by traffic load, and other influence factors such as number of lanes, etc. Haraldsson 2007 uses a dynamic model with a lag cost variable among the regressors which allows to derive both a short-run and a long- run elasticity.

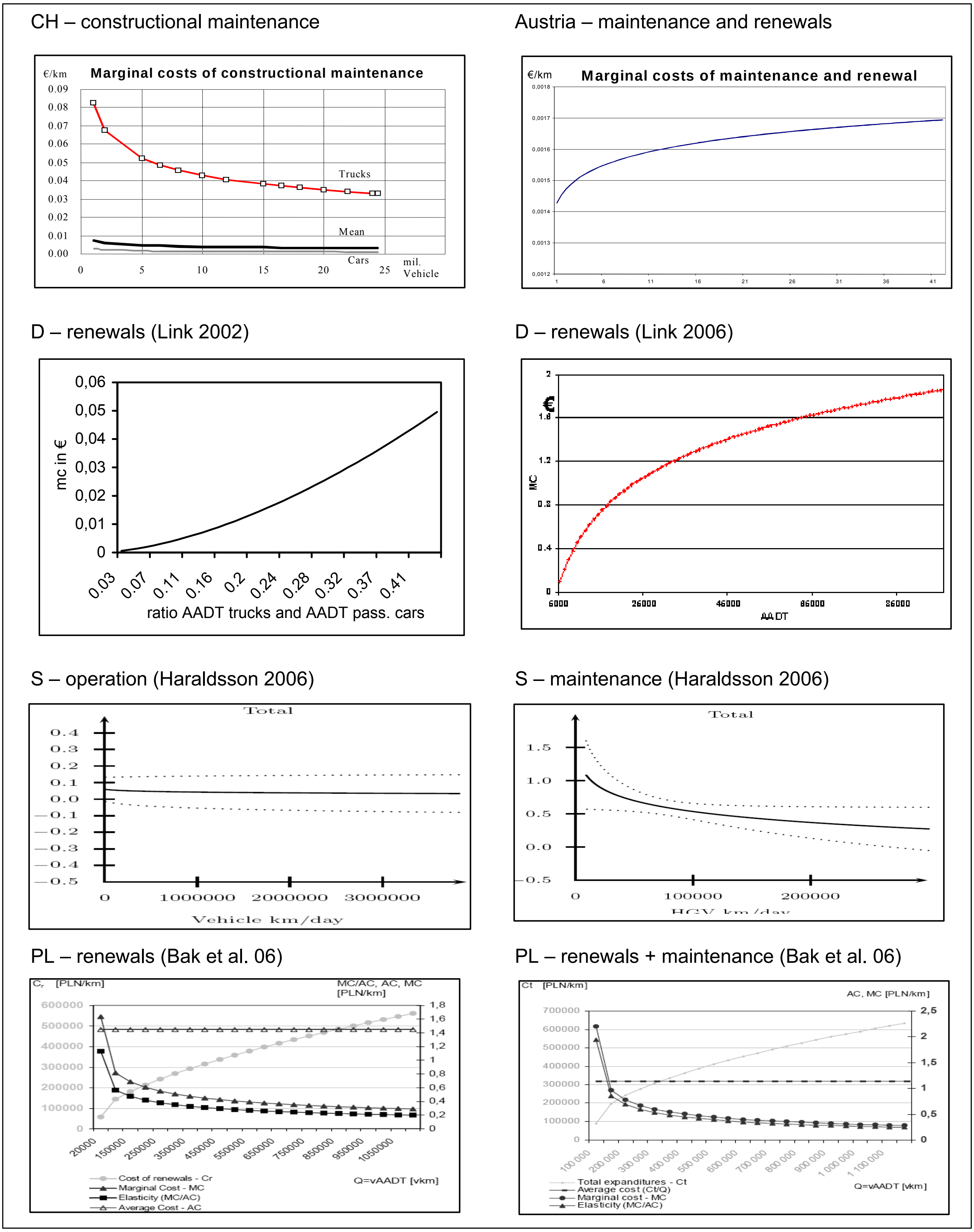
Most of the studies have derived non-linear marginal cost curves, with weaker non-linearities for increasing traffic volumes. The mean cost elasticity (e.g. the ratio between marginal and average costs) is generally below 1 (see table 1), suggesting that infrastructure cost charges based on marginal costs would not recover full costs[2].

The cost elasticity is highest for renewals and lowest for road operation with maintenance ranging between the two, indicating that the ratio between MC and AC decreases with a decrease of time horizon of the road measure. Furthermore, there is some evidence that road operation, e.g. measures with less than a 1 year's horizon, seems to be a fixed cost activity. The average cost elasticity ranges between 0.12 and 0.69 for maintenance (with a value of 0.12 for Poland as an extreme value and 0.27 in Haraldsson 2007 being the short term eleasticity derived from a dynamic model) and between 0.57 and 0.87 for renewals. The variation of the cost elasticity across the studies is larger for studies which deal with maintenance costs than for those dealing with other types of infrastructure measures which might hint at differences in defining and quantifying maintenance expenditures.

[1] Some studies also argue that it is reasonable to assume prices to be the same over the sections.

[2] Except the Austrian study which obtained a cost elasticity slightly above 1.

Figure 1: Marginal cost curves obtained by available studies



The majority of available econometric research (Sedlacek et al. 2002, Schreyer et al. 2002, Haraldsson 2006a, Haraldsson 2007, Bak et al. 2006) suggests a decreasing marginal cost curve (figure 1). Only an Austrian study (Sedlacek et al. 2002) and a German study (Link 2006, which is the only study based on a full system of translog model and factor input equations) found an increasing marginal cost curve. Both studies refer to renewals (the Austrian study analyses the sum of maintenance and renewals). However, it remains open for further reserach whether the differences in the shape of MC curves are caused by different types of road measures or by different methodological approaches.

It appears that due to multicollinearity problems econometric models have so far failed to estimate marginal costs for different types of vehicles. Most studies (Sedlacek et al. 2002, Schreyer et al. 2002, Haraldsson 2006a, Bak et al. 2006) use vkm of total traffic as explanatory variable, Haraldsson 2006 and 2007 estimates a model with the AADT of trucks and passenger cars, and Link 2006 uses truck-vkm. This implies that marginal cost estimates are rather “average” MC estimates. For the purpose of infrastructure charging these average MC estimates need further to be differentiated by using allocation factors from engineering knowledge or from expert opinion.

Table 1: Comparison of econometric cost function studies for road infrastructure

Source	Sedlacek et al. 2002	Schreyer et al. 2002		Link 2002	Haraldsson 2006a		Bak 2006		Link 2006	Haraldsson 2007	
Country	Austria	Switzerland		Germany	Sweden		Poland		Germany	Sweden	
Type of infrastructure	Motorways	Motorways + main roads		Motorways	All roads		National roads		Motorways	All paved roads	
Type of measure	maintenance + renewals	operational maintenance	constructional maintenance	renewals	operation	maintenance	maintenance	renewals	renewals	operation	maintenance
Traffic volume	total vkm	total vkm	total vkm	ratio trucks/ pass. cars	total vkm	HGV vkm	total vkm	total vkm	vkm trucks	total vkm	HGV vkm
Model											
a) single-equation, log-linear	x	x	x				x	x		x	x
b) single-equation, Translog				x							
c) single-equation, reduced Translog					x	x					
d) multi-equation Translog									x		
Cost elasticity											
a) fixed	x	x	x				x	x		x	x
b) variable				x	x	x			x		
MC curve											
a) decreasing		x	x		x	x	x	x			x
b) increasing	x			x					x		
Cost elasticity (mean)	1.046	0.69	0.71	n.a.[1]	0.05	0.58	0.12	0.57	0.87	-0.05 [2]	0.27

[1] Not sensible since the marginal cost curve refers to the ratio between trucks and passenger cars. - [2] Not significant.

Source: GRACE Deliverable 5.

2.1.2 Duration approaches

Amongst the duration approaches the best known and most widely used instrument for allocating road wear costs to different vehicles is probably the fourth power rule. It is based on the AASH(T)O-tests that were conducted in USA in the 1950/60es (see Highway Research Board 1961). According to this rule road wear, and consequently the corresponding marginal cost, is proportional to the number of vehicle equivalence factors (standard axles). An axle with load A thus causes a damage/cost corresponding to $(A/B)^4$ times the damage/cost caused by axle load B.

However, this rule is subject to some questions. First, it is not obvious that the power should be 4 in every case, even though it might be the best choice in general. The power varies with the type of distress that is in focus. Furthermore, the power can be expected to vary with road quality, road design[3], climate and several other facts (Hjort 2007). Second, the static axle load is not sufficient to explain road wear which is also influenced by dynamic axle loading. When the vehicle is moving, unevenness of the road will cause the vehicle to move up and down. "The magnitude of this dynamic variation depends on the vertical dynamics of the vehicle, including such factors as the mass and stiffness distribution of the vehicle structure, payload mass distribution, suspension and tyres, and on the road surface's longitudinal profile and the speed of the vehicle." (Hjort 2007, p.7) The magnitude of dynamic loads is mostly expressed as the Dynamic Load Coefficient (DLC). This measure essentially expresses load variation around the static load, and considers also new technical developments at vehicles such as road-friendly suspensions. The magnitude of this coefficient is 5-10 percent for well damped suspensions and 20-40 percent for less road friendly suspensions. Apart from this, the different ways to place axles in relation to each other might have an important role. It is for instance not proper to treat the distress caused by a tandem or triple axle as simply the sum of the distress from two different axles, since the distance between the axles is an important factor (Hjort 2007, pp. 7-8[4]).

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[3] One point of criticism stated regarding the design of the AASH(T)O tests was that roads were over-dimensioned.

[4] For a more detailed discussion on the impacts of axle configurations and road-friendly suspensions see also NERA 2000.

The opportunities to conduct large-scale experiments such as the AASH(T)O road test are rather limited.[5] Therefore, Newbery 1988 has developed an analytical approach which is known as the so-called fundamental theorem and which can be considered as a first formulation of the duration approach. The basic assumption of the duration approach is that the length of an interval between two renewal measures depends on the aggregate of traffic that has used a certain section. The major output from Newbery 1988, the so-called fundamental theorem, states 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[6], the marginal cost of pavement resurfacing is exactly equal to the average resurfacing cost and the road damage externality[7] is zero, e.g. the cost elasticity MC/AC equals 1. 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 the lifetime 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.

Three recent Swedish studies apply a more refined approach (table 2). In these studies the MC is computed as a function of a *deterioration elasticity* [8] and the average cost. Lindberg 2002 takes into account that the number of standard axles which a road can accommodate after all is a function of the actual, not the predicted traffic volume. Adding or subtracting vehicles to

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[5] Newbery 1988 estimates that a replication of the AASHTO road test would cost over $300 million at 1980 prices. Note, however, that modern technical equipment has meanwhile been available which enables to assess the validity of the fourth power rule. Another workpackage of CATRIN explores the possible framework of this type of analysis.

[6] 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.

[7] 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).

[8] The deterioration elasticity is a measure of the responsiveness in pavement lifetime to a change in average traffic intensity.

the original prediction will therefore affect the timing of a reinvestment and there is, consequently, a marginal cost associated with variations in traffic volume. While Lindberg 2002 assumes that the road is renewed as soon as a pre-defined terminal value is reached, Haraldsson 2006b bases the estimation on the observed intervals between two renewals. In contrast to Lindberg 2002 which uses standard axles as explanatory variable, Haraldsson 2006b includes the AADT of HGV and passenger cars, e.g. two traffic variables into the model. Furthermore, Haraldsson 2006b allows for random elements in the lifetime function by using a Weibull distribution. As long as the lifetime function is deterministic, the age distribution of roads is uniform. This implies, as is shown by Lindberg 2002, that the marginal cost is computed as the deterioration elasticity times the average cost. Assuming a Weibull distribution however implies that this should be adjusted by a factor relating from the age distribution of roads. In Haraldsson 2007 this factor is estimated to be 0.83 indicating that the assumption of Weibull distributed lifetimes leads to lower MC than would have been the case if a deterministic lifetime function had been assumed.

Table 2: Characteristics and results of the duration approach studies

Source	Lindberg 2002	Haraldsson 2006b	Haraldsson 2007
Model with age distribution of roads	x	x	x
Model with climate effect	-	x	x
Data on optimal renewal cycles	x	-	-
Data on observed renewal cycles	-	x	x
MC curve	increasing	decreasing	decreasing
cost elasticity (mean)	0.8	0.039	0.033

The studies presented in table 2 are first empirical analyses of this type of methodology. Differences between studies relate to the shape of the cost curve and the value of the deterioration elasticity, pointing out the need to conduct further analyses of this type, ideally with improved databases. Interestingly, the recent studies from 2006 and 2007 do not only yield a different shape of the marginal cost curve (decreasing) but differ also considerably from Lindberg 2002 with respect to the mean cost elasticity (0.8 in Lindberg 2002[9], 0.039 and 0.33 in Haraldsson 2006b and 2007 respectively). The deterioration elasticity in Haraldsson 2006b and 2007 is very low. A probable explanation for that is failure to control for different

[9] A mean cost elasticity of 0.8 for renewals seems to be supported both by econometric and by fully allocated cost studies. For MC studies see: Link 2006 (0.87), Bak et al. 2006 (0.57), Scheyer et al. 2002 (cost elasticity for constructional maintenance which comes close to renewal work: 0.71), Sedlacek et al. 2002 (1.046). For FAC studies: The Danish study assumes that between 50% and 70% of reconstruction costs vary with traffic volume, the Australian allocation study suggests that 45% of road rehabilitation costs are weight-dependent. The UK allocation study even assumes that 100% of reconstruction and resurfacing costs are weight-dependent.

pavement quality (thickness) in the empirical analysis. High traffic roads generally have a thicker pavement than low traffic roads. If this fact is not taken into account, it might seem like traffic only has a small impact on pavement lifetime.

Due to the type of data needed to apply the duration approach, most engineering-based studies provide marginal cost estimates per ESAL-km[10] and reflect the damaging behaviour of different weight classes better than the currently available econometric studies. For pricing policy the results of this type of studies need to be aggregated into weight classes of vehicles, in contrast to the econometric studies discussed in section 2.1.1 where the estimates need to be further disaggregated.

2.2 Fully allocated cost studies (FAC studies)

Although not appropriate for efficient infrastructure charging, fully allocated cost studies are worthwhile to be analysed for the purpose of CATRIN for several reasons. First, some of these studies categorise total costs into fixed and variable elements, and the latter category is of interest for estimating marginal costs (see Link et al. 2007). Second, the available fully allocated cost studies use a variety of allocation methods to apportion different cost elements to different vehicle categories. A thorough analysis of these methods and a comparison of the allocation factors used to allocate variable costs can support the necessary disaggregation of the available “average” existing MC estimates[11].

FAC studies aim to achieve recovery of total costs. The most common approach used in these studies is a top-down procedure where total costs are split up into different categories which are allocated to vehicle types by using different allocation factors. A second, not so widespread approach is to use game theory for allocating joint costs to vehicle types or user groups (club approach), mostly combined with a top-down allocation procedure for those cost elements which are considered as attributable costs. A third category are incremental cost and avoidable cost studies which attempt to identify the additional costs (incremental cost approach) or the avoidable costs (avoidable cost approach) which occur when adding

[10] Exceptions are Haraldsson 2006b and 2007 where MC figures for two types of vehicles are provided.

[11] However, not all of the fully allocated cost studies explicitly distinguish between fixed and variable cost elements. There are several studies which use different categorisation approaches and apply allocation factors to apportion these categories to vehicle types. Naturally, the methods and factors used in such studies are more difficult to evaluate under the aspect whether they can be used to disaggregate “average” marginal costs.

(subtracting) a group of users or a class of vehicles. These approaches can be interpreted as a discrete approaching of marginal costs, even though these studies aim at full cost recovery.

Table 3: Characteristics of road cost allocation studies

Country	AUS	US	CH	DEN	FIN	GER[1)]	GER[2)]	NL	UK	SWE
Official study	√	√	√			√	√		√	
Scientific and empirical back-ground studies	√	√	√			√	√	√	√	√
Repeated studies	√	√	√				√		√	
Overall methodology										
- top-down	√	√	√	√	√	√	√	√	√	√
- club approach for joint costs						√				
- incremental costs		√								
Cost/ expenditure categories	7	5	6	5	6	21	3		17	8
No. of vehicle categories	33	6	30	6		6	6	27	37	10
No. road types	2	2	3	2		2	2	2	4	3

[1)] Study conducted on behalf of the transport ministry to estimate the level of the German HGV charge. – [2)] Studies conducted on agreed methodology as official studies of the transport ministry until 1991.

Sources: Denmark: COWI 1994. Finland: LT Consultants. Germany: DIW 2000, Rommerskirchen et al 2002. Sweden: Hansson 1996. Netherlands: DHV/Tebodin 1992, Vermeulen et al. 2004. Australia: National Transport Commission 2005. UK: DETR 1997, NERA 2000. Switzerland: BFS 2003.

The review of FAC studies covers 9 countries (see table 3 for a summary of their main characteristics). In five countries (Australia, Germany, Switzerland, the UK and the US) these studies have an official character, e.g. form the basic document in the area of track cost allocation of the government. These official studies are conducted in a specified frequency, for example annually in Switzerland and the UK, or are repeated exercises, though not with a predefined frequency (Germany, the US and Australia), and there are frequent background studies aimed at improving the methodology and/ore the database used. The majority of studies analysed here are typical top-down studies. Exceptions are the FHA study in the United States which follows an incremental cost approach for the cost category construction of new bridges (apart from applying a top-down approach for other cost elements), and the German Maut study (Rommerskirchen et al. 2002) which uses a club approach for the allocation of joint costs.

The approaches to split up total costs into different sub-categories vary considerably between the available studies. Criteria used to categories costs are

- the type of road work (operating costs, maintenance costs, reconstruction and renewal costs, new investments),
- the time horizon of measures (capitalised costs versus non-capitalised running costs, fixed versus variable costs), and
- the type of assets (for example maintenance expenditures split up into those for pavement, for bridges etc.).

Often, more than one of these criteria is used (see table 4) and the number of sub-categories varies between the studies (see table 3: 3 categories in the German studies until 1991, 17 categories in the UK, 21 categories in the German Maut study). Another observation is that the number of vehicle categories used for the allocation procedure shows a great variance, ranging from 6 categories (usually passenger cars, light goods vehicles, Buses, and a few categories of HGV such as rigids with/without trailer, artics) up to 27 (NL), 30 (Switzerland), 33 (Australia) and 37 (UK) vehicle types.

Table 4: Allocation procedures in fully allocated road cost studies

Country	Cost category	Share (%) of costs allocated by …												
		vkm	ESALs 4th power	ESALs 2nd power	CoA[1)]	AGM	max gross weight	total weight-dependent	PCU	vehicle length-km	total capacity-related	Fixed costs	non-attributable costs	Others
Australia	Servicing and operating expenses	100						0			0			
	Road pavement & shoulder maintenance													
	- routine					37		37	37		37		26	
	- periodic					60		60	10		10		30	
	Bridge maintenance and rehabilitation					33		33			0		67	
	Road rehabilitation					45		45			0		55	
	Low cost safety/traffic improvements	80						0	20		20			
	Pavement improvements		45					45			0		55	
	Bridge improvements							0	15		15		85	
	Land acquisition, earthworks etc.	10						0			0		90	
	Other miscellaneous activities							0			0		100	
United States	Pavement costs for new lanes													
	- base facility							0	100		100			
	- to accomodate future axle loads		100					100			0			
	Pavement reconstruction, rehabilitation, resurfacing (3R)													
	- load related		100					100			0			
	- related to climate, age etc.	100						0			0			
	Bridges													
	- construction costs													incre-mental cost approach
	- replacement costs													
	- major rehabilitations													
	- other costs													
	System enhancement costs (safety)													
	- construction costs								100		100			

Country	Cost category	Share (%) of costs allocated by …										Fixed costs	non-attributable costs	Others
		vkm	ESALs 4th power	ESALs 2nd power	CoA[1)]	AGM	max gross weight	total weight-dependent	PCU	vehicle length-km	total capacity-related			
	- other costs	100												
	Other attributable costs[2)]	100						0			0			
Switzerland	Operating costs I (administration, signalling, traffic management)	100						0			0			
	Operating costs II (operational maintenance)	100						0			0			
	Capacity costs (costs with no relation to road use, fixed costs)							0		100	100			
	Weight-dependent costs I (45% of constructional maintenance costs caused by HGV)				100			100			0			
	Weight-dependent costs II (investment costs caused by HGV)		100					100			0			
	Interests on annual surplus/deficit							0			0			
Denmark[3)]	Investment	45 (80)						0		15 (5)	15 (5)			
	Reconstruction	25 (10)	45 (40)					45 (40)			0	30(50)		
	Winter maintenance	30 (30)						0		20 (20)	20 (20)	50 (50)		
	Other maintenance	20 (20)						0		10 (10)	10 (10)	70 (70)		
	Administration	30 (20)						0			0	70 (80)		
Finland	Winter maintenance	5						0			0	95		
	Maintenance of paved roads	50	25					25			0	25		
	Maintenance of light-paved roads	25	50					50			0	25		
	Maintenance of gravel roads	25	35					35			0	40		
	Traffic guidance & information	30						0			0	70		
	Landscaping and sanitation							0			0	100		
	Bridges	25	25					25			0	50		
	Ferries	20	5					5			0	75		
Germany[5)]	capacity costs							0	100		100			
	costs of traffic police	100						0			0			

Country	Cost category	Share (%) of costs allocated by …										Fixed costs	non-attributable costs	Others
		vkm	ESALs 4th power	ESALs 2nd power	CoA[1)]	AGM	max gross weight	total weight-dependent	PCU	vehicle length-km	total capacity-related			
	pavement maintenance		100					100			0			
	pavement renewals		100					100			0			
Germany [6)]	Land costs							0	100		100			
	tracking/drainage							0	100		100			
	base layer – new construction	73[*)]						0	27		27			
	base layer – maintenance		100					100			0			
	Binding layers – new construction	100[*)]						0			0			
	Binding layers – maintenance		100					100			0			
	overlays – new construction							0	100		100			
	overlays – maintenance		100					100			0			
	tunnels – new construction	45+5[5)]						0	50		50			
	tunnels – maintenance	80 + 20[5)]						0			0			
	bridges	15[5)]						0	85		85			
	equipment	33						0	67		67			
	nodes, branches – new construction	15+20[6)]+15[5)]						0	50		50			
	nodes, branches – maintenance	15+10[5)]	35					35	40		40			
	other engineering work	33						0	67		67			
	administration, police	30						0	70		70			
	operational maintenance	35+15[5)]						0	50		50			
Netherlands	Construction costs – fixed part (89%)							0			0			
	Motorways and provincial roads							0	30[7)], 70[8)]		30[7)], 70[8)]			
	Municipal roads							0	100[7)]		100[7)]			
	Construction costs – variable part (11%)		100					100			0			
	Maintenance costs – fixed part (70%)							0						
	Motorways and provincial roads							0	30[7)], 70[8)]		30[7)], 70[8)]			
	Municipal roads							0	100[7)]		100[7)]			

Country	Cost category	Share (%) of costs allocated by …										Fixed costs	non-attributable costs	Others
		vkm	ESALs 4th power	ESALs 2nd power	CoA[1]	AGM	max gross weight	total weight-dependent	PCU	vehicle length-km	total capacity-related			
	Maintenance costs – variable part (30%)		98	2				100						
	Costs of land use							0			0			
	Motorways and provincial roads							0	30[7], 70[8]		30[7], 70[8]			
	Municipal roads							0	100[7]		100[7]			
	Operation costs	100						0			0			
United Kingdom	Capital expenditure						15	15	85		85			
	Maintenance expenditures							0			0			
	Long life pavements		100					100			0			
	Resurfacing		100					100			0			
	Overlay		100					100			0			
	Surface dressing	20				80		80			0			
	Patching and minor repairs		80			20		100			0			
	Drainage	100						0			0			
	Bridges and remedial earthwork					100		100			0			
	Grass and hedge cutting	100						0			0			
	Sweeping and cleaning	50						0			0			50[9]
	Traffic signs and pedestrian crossings	100						0			0			
	Road marking	10				90		90			0			
	Footways, cycle tracks and kerbs					50		50			0			50[9]
	Fences and barriers	33				67		67			0			
	Winter maintenance & miscellaneous	100						0			0			
	Street lighting	50						0			0			50[9]
	Police and traffic warden	100						0			0			
Sweden	Investments – federal roads		21					21	79		79			
	Investments – municipal roads		26					26	74		74			

Country	Cost category	Share (%) of costs allocated by …										Fixed costs	non-attributable costs	Others
		vkm	ESALs 4th power	ESALs 2nd power	CoA[1]	AGM	max gross weight	total weight-dependent	PCU	vehicle length-km	total capacity-related			
	investments – private roads		8					8	92		92			
	Increase in bearing capacity		100					100			0			
	Maintenance/operation federal roads:										0			
	Winter road maintenance	5						0			0	95		
	Paving maintenance	75						0			0	25		
	Bridges	20						0			0	80		
	Ferries & bridge operation	5						0			0	95		
	Gravel road maintenance	35						0			0	65		
	Driving supervision, etc.							0			0	100		
	Traffic security	10						0			0	90		
	Improvement measures	25						0			0	75		
	maintenance/operation municipal roads:										0			
	paving maintenance	40						0			0	60		
	winter maintenance	5						0			0	95		
	bridges	20						0			0	80		
	other							0			0	100		
	maintenance/operation private roads	6						0			0	94		

Coefficient agressivite: This coefficient is calculated for each vehicle type based on the empty weight, the average load and a weigh-in-motion factor. [2)] Grading, drainage, pavement width, ridesharing programs and facilities, weigh stations. – [3)] Figures for motorways and trunk roads. Figures for principal and communal roads are given in brackets. - [4)] % of vehicle category in total costs used to allocated this cost category. – [5)] Studies conducted on agreed methodology as official studies of the transport ministry until 1991. [6)] Study conducted on behalf of the transport ministry to estimate the level of the German HGV charge. – [7)] PCUs at 60 km/h. – [8)] PCUs at 100 km/h. – [9)] Only allocated to HGV>=12t max GVW.- [10)] only allocated to passenger cars & others. – [11)] Allocated to pedestrians, except motorways.

Sources: Denmark: COWI 1994. Finland: LT Consultants. Germany: DIW 2000, Rommerskirchen et al 2002. Sweden: Hansson 1996. Netherlands: DHV/Tebodin 1992, Vermeulen et al. 2004. Australia: National Transport Commission 2005. UK: DETR 1997, NERA 2000. Switzerland: BFS 2003.

2.2.1 Indications on cost variability and weight-dependent costs

As mentioned before, an important information from FAC studies is the share of variable costs and weight-dependent costs. Table 5 and table 6 show figures from those studies which explicitly distinguish between fixed and variable elements of infrastructure cost (Denmark, Finland, Germany, Sweden, Netherlands) and from those which identify the share of weight-dependent costs respectively (Australia, the UK, Switzerland). This second group of studies is of particular interest for allocating costs to different weight classes of vehicles. Apart from this, they also provide some indication on cost variability because we can consider the share of costs allocated by weight dependent factors as a lower bound of cost variability.

Table 5: Indications on variable infrastructure costs in road cost accounting studies

Country	% of infrastructure costs assumed to be variable within cost category	
Denmark	Investment	100
	Reconstruction of motorways and trunk roads	70
	Reconstruction of provincial and municipal roads	50
	Winter maintenance	50
	Other maintenance	30
	Administration of motorways and trunk roads	30
	Administration of provincial and municipal roads	20
	Total costs	**n.a.**
Finland	Winter maintenance	5
	Maintenance of paved roads	75
	Maintenance of gravel roads	60
	Traffic guidance & information	30
	Bridges	50
	Ferries	25
	Total road expenditures	19
	Total road maintenance expenditures	**21**
Germany (DIW)	**Total costs**	**15**
Sweden	Winter road maintenance	**5**
	Paving maintenance	**75**
	Bridges	**33**
	Ferries & bridge operation	**25**
	Gravel road maintenance	**60**
	Driving supervision, etc.	**10**
	Traffic security	**10**
	Improvement measures	**25**
	Total maintenance expenditures	**28**
NL (DHV/Tebodin 1992)	**Maintenance, operation expenditures, overheads**	**58**
NL (Vermeulen et al. 2004)	**Maintenance, operation expenditures**	**30**
Sources: Denmark: COWI 1994. Finland: LT Consultants. Germany: DIW 2000, Rommerskirchen et al 2002. Sweden: Hansson 1996. Netherlands: DHV/Tebodin 1992, Vermeulen et al. 2004.		

Naturally, different definitions of maintenance, rehabilitation and reconstruction, different classification criteria for cost components (type of road work, time horizon, purpose of expenditures) and a varying degree of differentiating these categories further hamper a comparison and generalisation of the figures shown in table 5 and table 6. Nevertheless, it can be concluded that between 21% and 30% of infrastructure costs are variable[12]. Weight-dependent costs make up between 33% and 46%[13].

Table 6: Indications on weight-dependent costs in road cost accounting studies

Country	% of costs assumed to be weight-dependent within cost category	
Australia	1 a) Routine road pavement & shoulder maintenance	37
	1 b) Periodic road pavement & shoulder maintenance	60
	2. Bridge maintenance	33
	3. Road rehabilitation	45
	4. Improvement of pavement	45
	Total expenditures	**46**
UK	Capital expenditure	15
	Reconstruction and resurfacing	100
	Haunching	100
	Surface dressing and skid treatments	80
	Patching and minor repairs	100
	Bridges and remedial earthwork	100
	Road marking	90
	Footways, cycle tracks and kerbs	50
	Fences and barriers	67
	Total road expenditures	**33**
Switzerland	Investment costs[1)]	7
	Constructional maintenance	45

[1)]Interest and depreciation for new construction, expansion, improvement, land acquisition.
Sources: Australia: National Transport Commission 2005. UK: DETR 1997, NERA 2000. Switzerland: BFS 2003.

2.2.2 Allocation procedures and allocation factors used

Table 7 shows the variety of allocation factors applied in the studies reviewed. Three different groups of factors are used:

- First, vkm which distribute costs proportionally to the use of roads by each vehicle type. They are mostly used for those cost components which are considered to vary with road use, but for which differences in cost causation (damages) between vehicle types are not apparent. Examples are service and operation expenditures, costs of traffic management schemes, police, road lighting, traffic signs etc. but also parts of winter maintenance and

[12] Outliers seem to be an earlier Dutch study which derived a share of 58%, and an earlier German study which, however, has used a cost-based approach with capitalised investments, and which suggests a share of 15%.

climate related pavement costs (see table 4). In some studies vkm are also used to allocated fixed costs.

- Second, weight dependent factors such as axle-load km, mostly applied according to the AASH(T)O road test figures as fourth-power rule, in some studies also as second power rule for some cost categories, and other weight-related measures such as maximum and average gross vehicle weight. Cost categories which are considered to be weight dependent are (parts of) pavement maintenance & reconstruction, bridge maintenance & reconstruction and, in some studies, those parts of the construction costs for bridges and pavements which occur to accommodate higher axle-loads (Vermeulen et al. 2000).
- Third, capacity related allocation factors such as PCUs (again in various forms, see for example in Vermeulen et al. 2000) and equivalence factors related to the length of vehicles. Capacity related factors (PCUs) are usually applied to distribute fixed costs, the costs of earthwork and drainage and land costs, and - in some studies - to allocate the costs of base facilities. They are also applied to allocate different proportions of maintenance and reconstruction costs.

Table 7: Allocation factors used in fully allocated road cost studies

Allocation factors	US	AUS	CH	DEN	FIN	GER[1)]	GER[2)]	NL	UK	SWE
Vehicle-km	√	√	√	√	√	√	√	√	√	√
Axle-loads – 4th power	√	√	√	√	√	√	√	√	√	√
Axle-loads – 2nd power								√		
AGM		√							√	
Coefficient agressivite[3)]			√							
Max. gross vehicle weight									√	
PCU	√	√				√	√		√	√
PCU at 60 km/h								√		
PCU at 100 km/h								√		
Vehicle length			√	√						

[1)] Study conducted on behalf of the transport ministry to estimate the level of the German HGV charge. – 2) Studies conducted on agreed methodology as official studies of the transport ministry until 1991. 3) This coefficient is calculated for each vehicle type based on the empty weight, the average load and a weigh-in-motion factor.

Sources: Denmark: COWI 1994. Finland: LT Consultants. Germany: DIW 2000, Rommerskirchen et al 2002. Sweden: Hansson 1996. Netherlands: DHV/Tebodin 1992, Vermeulen et al. 2004. Australia: National Transport Commission 2005. UK: DETR 1997, NERA 2000. Switzerland: BFS 2003.

[13] Note, that these shares strongly depend on the type of road (see the variance of the UK figures from 26% up to 42%). Furthermore, the Australian figure relates to maintenance expenditures only, e.g. would be lower if total

In the following we will discuss the two most important allocation factors, the AASH(T)O factors and the PCUs, in more detail. The application of the AASH(T)O factors to allocate weight-dependent costs is straightforward. The factor is obtained by summing up the fourth power of the ratio between effective axle load and the 10t standard axle load for each axle of a given vehicle. Despite of this clear calculation rule there exist country-specific differences in the factor values. These differences arise from the different disaggregation of mileage data by vehicle weight classes and the measurements of vehicle loadings as well as from the distribution of total weight to the axles. Furthermore, the fact that axle configurations such as tandem or triple axles cause higher road damages than single axles is reflected in national allocation practices in different ways. For example, the German Maut study (Rommerskirchen et al. 2002) assumes for tandem and triple axles other standard weights (18.35t and 24t respectively) than for single axles. The Swiss and the Dutch allocation procedures consider axle configurations while the UK procedure treats each axle as a single axle.

As mentioned above, the AASH(T)O road test factors have been subject of controversial discussions since their appearance, and simulation exercises and other engineering research has deemed to verify or revise the figures. This is reflected in some countries' cost allocation practice by applying other powers than the fourth power. One example is the Dutch study (Vermeulen et al. 2004) where for a part of maintenance costs the second power instead of the fourth power is applied. Another example is Switzerland which for a long time has used the 2.5th power (BFS 1985). In BFS 2003 a revision of the Swiss road cost allocation was suggested based on a background study of the University of Lausanne (LAVOC 2000) which analysed the feasibility of applying the former axle-load factors. With this revision, the weight-dependent part of constructive maintenance is allocated by using a so-called Coefficient agressivite (CoA, instead of the former exponential axle-load factors) which is calculated for each vehicle type based on the empty weight, the average load and a weigh-in-motion factor. The weight-dependent investment costs are distributed by a revised proportional axle-load factor.

In contrast to the AASH(T)O factors, PCU figures vary between countries not only to different disaggregations of vehicle mileage data in transport statistics but also due to differences in the underlying concepts. It appears that for the PCU figures, a category which originates from road engineering disciplines such as traffic and road capacity planning, any commonly agreed and applied method does not exist. Depending on the underlying concept,

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road expenditures were considered.

PCUs are based on average speed, traffic density, average distance between vehicles within the traffic flow, safety distances and delays. The impact of heavier vehicles on taffic flow is considered by vehicle characteristics such as length and the ratio between weight and engine power on the one hand, and the existence and length of gradients, the share of trucks in the traffic flow, the number of lanes and traffic density on the other hand (see Al-Kaisy et al. 2002, Rodriguez and Benekohal 2004). For example, the PCU figures used in the German cost allocation studies until 1992 (table 8) were based on the assumption that differences in road occupancy between vehicle types are solely caused by different speeds and not by space or length requirements. The PCU factors were derived in the late 60es within studies on the different speeds of vehicle classes at gradient sections. The German Maut study (Rommerskirchen et al. 2002) has revised these figures and obtained lower values for heavier vehicles. Their figures appear to follow the concept of dynamic space requirements of different vehicle types as suggested in Switzerland, however, there seems to be no underlying study and/or a comprehensive empirical database.

Table 8: PCU figures used in Germany

Vehicle category	Cost allocation studies of the Transport Ministry until 1992	German Maut study
Passenger cars	1.0	1.0
Buses	3.0	2.5
Motorcycles	0.5	0.5
Goods vehicles		
below 3.5 t	1.7	1.2
3.5 – 12t	2.2-2.7	1.5
12-18t	4.3	2.5
18 – 28t	5.8	3.5
28 – 33 t	5.8	4.0
above 33t	5.8	4.5
Articulated vehicles	6.0	4.5
Other vehicles	6.0	2.0
Sources: DIW 1978, DIW 1980, DIW 1983, DIW 1990, DIW 1992, Rommerskirchen et al. 2002.		

In the UK, PCU figures were derived with two modelling approaches:

- Junction modelling (3 types: give-way junctions, traffic signals, roundabouts) where the impact of various vehicle types on the saturation flows of different junction types is assessed (table 9).

- Transportation modelling where PCUs are used to add up vehicle matrices of different vehicle types to estimate their combined impact on speeds and journey times[14] (see table 9, last 4 columns).

NERA 2000 suggests to explore an alternative, more sophisticated approach to determine and use PCU values in road cost allocation. This approach would use speed-flow curves to estimate the impact of traffic level and traffic composition on speeds whereby it is assumed that the presence of heavy goods vehicles affects the maximum road capacity of rural and suburban roads only. The approach implies that the effects of HGVs are only significant at or around the flow conditions in which queuing is expected to occur.

Table 9: PCU figures used in different junction models and in traffic models in the UK

Vehicle type	PCUs in junction models		PCUs in traffic models			
	PICADY & OSCADY[1)]	**ARCADY[2)]**	**Rural roads**	**Urban streets**	**Round-abouts**	**Traffic signals**
Cars and LGV (4 tyres)	1.0	1.0	1.0	1.0	1.0	1.0
Medium goods vehicles (2 axles >4 tyres)	1.5	2.0	3.0	1.75	2.8	1.75
Heavy goods vehicles (>2 axles)	2.3	2.0	3.0	2.5	2.8	1.75
Buses	2.0	2.0	3.0	3.0	2.8	2.25
Motorcycles	0.4	0.0	1.0	0.75	0.75	0.33
Bicycles	0.2	0.0	0.5	0.33	0.5	0.2

[1)] PICADY: model for give-way junctions, OSCADY: model for junctions with traffic signals. [2)] ACADY: model for roundabouts.

Sources: For the junction models TRL, for the PCU figures in traffic models: Research on Road Traffic, table 6.1, chapter 6, HMSO 1965.

In a Danish cost allocation study (COWI 1994) applies space-dependent PCU figures whereby lorries have a factor of 2, buses a factor of 3 and articulated vehicles a factor of 4.

In the Netherlands, two types of speed dependent PCU values are used for cost allocation. 30% of fixed maintenance costs as well as construction and land use costs for highways, motorways and provincial roads are allocated by PCU figures which consider a safety distance of 30 km between vehicles which is required at an overall speed of 60 km per hour. 70% of variable maintenance costs are distributed by PCU values which are based on a safety distance of 50 m required at 100 km per hour[15] (see Vermeulen et al. 2004).

[14] This, however, implies the availability of PCU figures from other sources.

[15] For municipal roads 100% of these cost categories are allocated by PCU figures which consider a speed of 60 km per hour.

Table 10: PCU figures used in the Dutch allocation method

Vehicle type	PCU at 60 km/h	PCU at 100 km/h
Passenger car	1	1
Delivery van	1	1
Bus	1.2	1.1
Solo truck	1.2	1.1
Truck with trailer	1.4	1.2
Source: Vermeulen et al. 2004.		

The available PCU figures for Sweden stem from older sources and it is not clear whether they are solely based on speed or also on space or length requirements. Table 11 gives PCU figures taken from a work on road capacity at the end of the 50es, and those adopted by the Swedish Commission for Vehicle Taxation in 1965. Hansson 1996, which includes apart from a marginal cost estimation also a fully allocated cost study seems to use the UK PCU figures.

Table 11: PCU figures used in Sweden

Vehicle type	Nordquist 1958	Commission on Vehicle Taxation 1965
Passenger cars	1	1
Light goods vehicles (below 3t)	1	1
Bus	2.5	*)
Goods vehicles above 3t		
3-12t	2.5	2.0
above 12t		3.0
Vehicle combinations	3.5	
Trailers		
below 3t		0.5
3t-12t		1
above 12t		2.0
*) Buses are included in the respective weight classes of trucks and trailers.		
Sources: Nordqvist 1958, Swedish Commission on Vehicle Taxation.		

2.3 Open issues arising from the review of studies

Research on estimating the marginal costs of operating, maintaining and renewing roads has made remarkable progress in understanding marginal costs in different modes over the recent years. The body of available studies allows to draw conclusions on the degree of cost variability for cost categories such as renewals, maintenance and operation (see Link et al. 2007). Furthermore, at the current frontier of research cost elasticity figures can be used for pricing policies. Here the studies provide evidence that the mean value of the cost elasticity is generally below 1, whereby the values increase with the time horizon of the road measure (operation, maintenance, renewal).

Outstanding issues to be solved relate to three subjects. First, MC studies need to be further developed in order to provide marginal cost estimates per vehicle types and weight classes. Currently, results are either too aggregated (econometric studies) or too disaggregated (engineering-based approach). Second, more evidence on the shape of the MC curve (decreasing versus increasing) is needed. Apart from this, there is no sufficient evidence to draw general conclusions on MC estimates for different types of roads. Third, a further important issue relates to the allocation factors used in FAC studies such as the AASH(T)TO factors and PCU values. Given the widespread use of the AASH(T)O factors it were desirable to generate new empirical evidence on the validity of the 4^{th} power rule and the impact which the development of vehicles and road designs might have. Similarly, more evidence on the PCU figures is important since the allocation of fixed costs remains a problem for pricing policy, for example in the discussion of HGV charge calculations by member states.

3 Rail

Traditionally, work on railway costs has focused on the characteristics of the vertically integrated railway. As a result of the restructuring, however, there has been a strong need to examine the interaction between operations and infrastructure for pricing purposes. Innovative econometric work has gradually come to inform the level of charges in some countries. However, significant issues regarding the estimation methodology and data availability remain.

At the margin, higher use of transport infrastructure results in an increase in wear and tear damage which implies associated costs of extra maintenance work and a bringing forward in time of renewal activity. Similar to marginal road costs, estimation of these marginal wear and tear costs can be split into two groups: **top-down approaches** and **bottom-up approaches** (Link and Nilsson 2005).

Top down approaches use data on costs of maintaining and/or renewing the infrastructure and estimate what proportion of these cost are variable with traffic. Two methods of doing this have been implemented in Europe: estimation of an infrastructure cost function using econometric techniques and cost allocation methods which allocate constituent parts of total cost to activities and then use engineering judgement to determine the variability of this cost to traffic. The econometric approach produces very disaggregate measures of marginal cost; it however requires data of sufficient quantity and quality to produce reliable estimates. The cost allocation method gives a measure of average variable cost which may differ from true marginal costs, and relies heavily on the judgement of engineers. However the approach is more easily undertaken and so is seen as a pragmatic alternative to estimating a cost function through econometric methods.

Bottom-up approaches rely on engineering models and judgement to determine the likely wear and tear impact of running an extra vehicle on each different component of the infrastructure network. A cost is then assigned to the resulting added wear and tear and this is the marginal cost. In principle this method would give a true measure of marginal wear and tear cost, as unlike top-down approaches, these are based on the need for maintenance and renewal activity rather than actual historical activity which maybe distorted by e.g. budgetary constraints. However in practice the models can rely on many tenuous assumptions and may not cover all aspects of wear and tear costs. For these reasons, in railway transport, bottom-up approaches are usually only used to allocate variable costs from the top-down models between vehicle types in a more disaggregate way than implied by the top-down models (see for example Booz, Allen and Hamilton, 2005 for a more detailed discussion of the UK approach).

3.1 Econometric studies

Innovative econometric work has emerged following the seminal paper by Johansson and Nilsson 2002 which has gradually come to inform the level of charges in countries such as Sweden. Table 12 shows the key empirical studies carried out in recent years. This host of research has been strongly motivated by the vertical separation of infrastructure and operations introduced by EU Directive 2001/14 and the call for more transparent charging systems based on some form of marginal cost pricing. This work has been funded mainly by EU research grants but, in some cases, directly by rail infrastructure managers. Even where they did not provide a financial contribution their role was of key importance by providing detailed databases relating to infrastructure characteristics and cost data. The following sections discuss the methodology and results of these studies in more detail.

Table 12: Summary of empirical studies on marginal rail infrastructure costs

Study	Country	Type of Author	Funding	In use
Johansson and Nilsson (2002)	Sweden	Academic	UNITE + BV	Yes
Johansson and Nilsson (2002)	Finland	Academic	UNITE + BV	-
Andersson (2006a and 2006b)	Sweden	Academic	GRACE	-
Tervonen and Idrstrom (2004)	Finland	Consultant	Finnish Rail Administration	Planned
Munduch et al (2002)	Austria	Academic	Austrian Railways	Planned
Gaudry and Quinet (2003)	France	Academic	SNCF	-
Marti and Neuenschwander (2006)	CH	Consultant	GRACE	-
Wheat and Smith (forthcoming)	UK	Academic	GRACE	-

3.1.1 Accounting for infrastructure characteristics, capability and condition

Table 13 shows that all the studies reported have sought to control for infrastructure variables, e.g. variables which describe the physical environment on which trains operate, such as the length, number, gradient and radii of tracks and the number of switches, tunnels and bridges on the track section. Many different variables have been used (based on what data is made available by the infrastructure manager) and the balance of variables between each category differs from study to study. It has been observed that marginal cost estimates between countries tend to differ substantially (below). However the average usage elasticities do not differ by the same scale and thus there must be strong differences between average costs by country. Accounting for infrastructure characteristics, capability and condition may provide an insight into these differences as they are clearly strong drivers of cost. For example, older sections of track in poor condition may require a significantly greater degree of maintenance than new tracks in good condition. Similarly, sections of track with complex signalling or a large number of switches will require a much greater level of on-going maintenance than other more straightforward sections.

The majority of studies has also attempted to include capability or quality measures. These measures refer to variables which characterise the performance capability and inherent capital investment in the infrastructure. This includes variables such as the type and grade of the rail (continuously welded rail versus jointed track and rail weight for example) and the maximum line speed and axle load capability of the track.

Only a few studies have succeeded in taking into account measures on the condition of assets. Such data is difficult to collect and apart from the ages of rails (UK, Sweden and Switzerland), sleeper (Sweden and Switzerland) and ballast (Sweden) there are no other variables available to the studies. Examples of variables that could conceivably become available are horizontal and vertical displacement measures and number of broken rails and other failures. The lack of variables detailing the condition of assets limits the potential for comparability between studies.

The processes adopted by the infrastructure manager will also impact on cost but no account has been taken of this issue in previous studies. For example, a determinant of the cost of doing maintenance and renewal is the possessions regime adopted e.g. closing a line versus working with a reduced timetable. This is difficult to examine since possession policies tend to be country wide, however there maybe differences depending on the number of running lines for each track section (e.g. single versus double track).

Table 13 Infrastructure characteristics, capability and condition measures used in econometric rail cost studies

Country	Great Britain	Sweden	Austria	France	Switzerland	Sweden	Finland
Study	Wheat and Smith (forthcoming)	Andersson (2006a)	Munduch et al (2002)	Gaudry and Quinet (2003)	Marti and N'schwander (2006)	Johansson and Nilsson (2002)	Johansson and Nilsson (2002)
Infrastructure characteristics	Track length Route length Length of switches	Track section distance Route length Tunnels Bridges Rail weight Rail gradient Rail cant Curvature Lubrication Joints Continuous welded rails Frost protection Switches Switch age Sleeper age Rail age Ballast age	Track section length Length of single-railed tunnels in meters Length of double-railed tunnels in meters Track radius Track gradient Length of the switches Station rails (as percentage of track length)	Number of track Apparatus Whether the track is electrified Route length Number of tracks, Automatic Traffic Control included or not	Track length Track distance (route length) Length of switches Length of Bridges Tunnels Level crossings Track Radius Track gradient Noise / fire protection Number of switches (by type) Shafts Platform edge	Track length Switches Bridges Tunnels	Track length Switches
Capability	Continuously welded rails Maximum line speed Maximum axle load	Rail weight Continuous welded rails Track quality class		Maximum line speed	Maximum line speed	Track quality index Secondary lines	Electrified Average speed
Condition	Rail age	Switch age Sleeper age Rail age Ballast age	Rail age		Rail age Sleepers age		
Source: Work carried out by Phil Wheat, ITS, University of Leeds.							

Finally, in the Austrian case study, interaction terms between usage and infrastructure characteristics and condition measure were tested. Some of the interactions between the characteristics and output were found to be statistically significant and remained in the final specification. This approach is very interesting, as this allows the usage elasticity to be a function of infrastructure characteristics, as opposed to the approach in the other studies where the elasticity is independent of infrastructure characteristics, capability and condition.

3.1.2 Methodological approach

Table 14 summarises the key methodological features of each study including the types of expenditure and the output indicators considered, the functional form used, whether a separate analysis of the effect of train and train-kms was carried out and whether input prices were included in the model specification.

Table 14: Methodological approaches used in econometric rail cost studies

Study	Country	Cost considered	Data type	Functional form	Number of trains/weight of trains distinction included	Input prices included
Johansson and Nilsson (2002)	Sweden	Maintenance	Panel (Pooled OLS)	Translog	×	×
Johansson and Nilsson (2002)	Finland	Maintenance and Maintenance plus Renewal	Panel (Pooled OLS)	Translog	×	×
Andersson (2006a and 2006b)	Sweden	Maintenance plus operations & Maintenance plus Operations plus Renewals	Panel (Pooled OLS and Random effects)	Translog	✓	×
Tervonen and Idrstrom (2004)	Finland	Maintenance and maintenance plus Renewal	Panel (Pooled OLS)	First order Double Log	×	×
Munduch et al (2002)	Austria	Maintenance	Panel (Pooled OLS)	Double log with interaction terms	×	×
Gaudry and Quinet (2003)	France	Maintenance plus operations	Cross section	Unrestricted Generalized Box-Cox	✓	×
Marti and Neuenschwander (2006)	CH	All maintenance, track maintenance plus operations, and maintenance plus renewals	Panel (Pooled OLS)	First order Double Log	×	×
Wheat and Smith (forthcoming)	UK	Maintenance	Cross-section	Double log with squared and cubic terms	✓	✓
Johansson and Nilsson (2002)	Sweden	Maintenance	Panel (Pooled OLS)	Translog	×	×
Source: Work carried out by Phil Wheat, ITS, University of Leeds.						

The vast majority of studies have only considered maintenance expenditure as the dependent variable. While precise definitions differ between countries, maintenance activity refers to processes which keep existing assets in working order. Renewals expenditure refers to activities which replace assets like-for-like following the end of their lives. Renewals data has in general been excluded because renewals expenditure tends to be ‘lumpy’ in nature which thus requires a time series of expenditures or data sufficiently aggregated to make analysis meaningful; and also because renewals expenditure depends much more on past as well as current traffic than maintenance expenditure.

To date there have been two approaches used in the econometric literature to modelling the impact of renewals. The first is regress renewal cost for one year against traffic for the same year and various infrastructure characteristics, capability and condition measures. Andersson 2006a examined renewals in Sweden and Marti and Neuenschwander 2006 examined "Contracting B" expenditure which includes some small scale renewals in Switzerland. Current traffic is likely to be correlated with past traffic and the inclusion of condition measures may proxy for the state of the assets in terms of life expired. However it is far from clear whether this is sufficient to yield an unbiased estimate of marginal cost.

The second approach is to use survival analysis. This requires data on traffic over the life time of the assets but does explicitly allow for the lumpiness of renewals activity. Essentially this approach models the probability that an asset will survive past a certain age conditional on a set of exogenous factors, in this case traffic. Similar to the approaches discussed for the road sector, a deterioration elasticity can be derived which examines the reduction in expected life of an asset given a change in traffic. This allows a marginal cost of traffic to be calculated. Andersson 2006b is the only study to apply this analysis to rail infrastructure. The author reports marginal costs in line with his analysis using the year-by-year regression approach. It should be noted that the data requirements are onerous and where traffic data has not been available in the Andersson 2006b study, assumptions regarding growth had to be applied to back cast traffic.

Even though some studies appear to consider expenditure on operations together with general maintenance this usually relates to maintenance-related activities such as snow clearing. In reality no work seems to have been done in explicitly quantifying the marginal cost of train planning and operations or of support services such as stations and depots.

It is interesting to note that only three studies considered both the number and weight of trains (gross tonne-kilometres) as explanatory variables. Gaudry and Quinet 2003 were able to show a significant difference between the impact of these two variables. Indeed, whereas the weight of trains is likely to be the more meaningful explanatory variable for maintenance costs the number of trains can be expected to have a stronger correlation with network planning and operation costs.

With the exception of Wheat and Smith (forthcoming) all studies considered constant input prices due to the limited availability of data and justified by the assumption that wages and material costs are relatively homogeneous within each country.

Functional form

It is desirable from a cost modelling perspective to choose a functional form such that there are minimum restrictions imposed on the underlying technology. However, the so called flexible functional forms, such as the translog cost function, have a problem in terms of the number of parameters that need to be estimated. This consumes degrees of freedom and this issue, coupled with the fact that many of the variables are highly correlated, can result in imprecise parameter estimates. Thus, not all studies have used the flexible functional forms, with the first order double log, constant elasticity form (Cobb Douglas) being the simplest alternative. The latter is more restrictive, in particular because it assumes constant cost elasticities.

Measures of output

Most studies used gross tonne-km as the single measure of output. This allows the MC cost for different vehicle weights to be established, but fails to allow for any other systematic variation in vehicle characteristics or for the additional operating costs incurred by planning and running additional trains (regardless of their weight or length).

As we will describe in section 3.2, engineering models assume that characteristics such as unsprung mass and the speed of the vehicle affect track wear. Indeed, Gaudry and Quinet 2003 have found evidence for statistically significant differences in the results for the impact of the weight of trains and the type of traffic. They find that, per tonne-km:

- freight trains are 2.44 as damaging as high speed passenger services and
- local passenger services are 0.18 times as damaging as high speed passenger services.

Wheat and Smith (forthcoming) tried to incorporate both passenger and freight gross tonne-km variables but find these do not yield robust parameter estimates. Data also exists in Sweden to analyse this distinction, however work to date has failed to produce robust estimates. This lack of agreement between studies could be due to methodological differences as Gaudry and Quinet 2003 use a generalised Box-Cox functional form as opposed to the double log used in the other studies. It would therefore seem useful to re-estimate models for the UK and Swedish data sets using the Box-Cox formulation. On the other hand, the French study had access to a very rich cross sectional data set (1500 track sections), which may be the key reason why such effects could be detected and reliably estimated.

Table 15: Calculation of the scaled usage elasticity for rail infrastructure

Study	Country	Proportion of Maintenance cost considered in the studies	Reported Total Usage Elasticity (Average)	Scaled Elasticity
Maintenance only				
Wheat and Smith (forthcoming) Model IV	Great Britain	45%	0.239	0.11
Wheat and Smith (forthcoming) Model VI	Great Britain	45%	0.378	0.17
Booz Allen & Hamilton (2005)	Great Britain	60%	0.28	0.17
Andersson (2006a)	Sweden	100% *	0.204	0.204
Marti and Neuschwander (2006) Model type 1	Switzerland	Not stated – 70% assumed	0.200	0.14
Marti and Neuschwander (2006) Model type 2	Switzerland	Not stated – 70% assumed	0.285	0.20
Tervonen and Idstrom (2004)	Finland	55% (of basic and special maintenance)	0.133-0.175	0.07
Munduch et al (2002)	Austria	Not stated (for track maintenance 70% assumed)	0.27	0.19
Gaudry and Quinet (2003)	France	Not stated (for track maintenance 70% assumed)	0.37	0.26
Maintenance and Renewals				
Andersson (2006a)	Sweden	100% *	0.302	0.302
Marti and Neuenschwander (2006)	Switzerland	Not stated – 70% assumed	0.265	0.19
Tervonen and Idstrom (2004)	Finland	66%	0.267-0.291	0.18

Note: Where the proportion of total maintenance cost considered in the respective study has not been provided in the paper a judgement was made as to the most appropriate proportion based on the description of costs in the paper and correspondence with the authors.

* From correspondence with author. This study, unlike Johansson and Nilsson (2002), examined maintenance/maintenance and renewal and not maintenance and operations/ maintenance, renewals and operations hence the 100% cost used.

Source: Link et al. 2007.

Estimates of marginal cost and usage elasticity

Table 15 shows the average elasticity of cost with respect to usage (usage elasticity) for a selection of countries. The elasticities differ considerably between studies. Link et al. 2007 constructed another measure of elasticity, called the scaled elasticity, by multiplying the average usage elasticity by the proportion of total maintenance (or maintenance and renewal) cost considered in the study. This gives a more comparable figure because, provided the elements of cost excluded from each analysis do not vary with usage, the scaled elasticities give the elasticity of total maintenance cost with respect to usage.

However, even the range of scaled elasticities is still very high (0.07 – 0.26 for maintenance; 0.18 – 0.302 for maintenance plus renewals). For maintenance expenditure only, Gaudry and Quinet 2003 come up with the highest scaled elasticity and Tervonen and Idstrom 2004 with the lowest although most models arrive at estimates in the 0.15 – 0.2 range.It must be noted that this computation was based on a limited amount of data and further information could produce a more robust scaled elasticity.

Table 16 shows that the range of marginal cost estimates is even wider than the range of usage elasticities. For example the marginal cost in Britain are over three times greater than those in Austria and between 6-10 times greater than those in Finland. Comparing the mean elasticity and/or marginal cost may be too simplistic, however, given the wide distribution of elasticities and marginal costs even within each of the samples. Thus small changes at the extremes of the sample (especially for track sections with very low traffic), may have a large effect on the averages computed.

One of the most consistent findings from econometric studies is that marginal costs are found to fall with usage. Not only this, for several studies they are initially very high with low usage levels but then fall very sharply, such that for medium and high tonnage levels marginal costs are very small. While there may be some economies of scale in maintenance activities this dramatic fall in marginal cost counters the engineering expectation that infrastructure wear and tear is roughly proportional to gross-tonne kilometers (assuming axle-load constant) (Booz Allen Hamilton and TTCI UK 2005).

Table 16: Results of empirical studies on marginal rail infrastructure costs

Study	Study Type	Country	Usage Elasticity	Evidence on behaviour of usage elasticity with usage	Average Marginal Cost (Euro per thousand gross tonne-km)(**)
Maintenance only					
Andersson (2006a)	Econometric	Sweden	0.204*	Falling	0.35
Wheat and Smith (forthcoming) (model IV)	Econometric	Great Britain	0.239*	Falling	1.246
Wheat and Smith (forthcoming) (model VI)	Econometric	Great Britain	0.378	**Falling and then increasing**	1.775
Marti and Neuenschwander (2006) Model Type 1	Econometric	Switzerland	0.200	Not tested	0.45
Marti and Neuenschwander (2006) Model Type 2	Econometric	Switzerland	0.285	Not tested	0.38
Johansson and Nilsson	Econometric	Sweden	0.1691*	Falling	0.143
Johansson and Nilsson	Econometric	Finland	0.167*	Falling	0.268
Tervonen and Idstrom (2004)	Econometric	Finland	0.133-0.175	Not tested	0.22
Munduch et al (2002)	Econometric	Austria	0.27	Not tested	0.55
Gaudry and Quinet (2003)	Econometric	France	0.37*	**Increasing**	Not reported
Booz Allen and Hamilton (2005)	**Cost Allocation**	Great Britain	0.28 for track maintenance	Not tested	1.768
Maintenance and renewals					
Andersson (2006a)	Econometric	Sweden	0.302*	Falling	0.79
Marti and Neuenschwander (2006)	Econometric	Switzerland	0.265	Not tested	0.97
Tervonen and Idstrom (2004)	Econometric	Finland	0.267-0.291	Not tested	
Booz Allen and Hamilton (2005)	**Cost Allocation**	Great Britain	0.19	Not tested	4.99
Renewals only					
Andersson (2006b)	Duration	Sweden	Not reported	Not tested	0.32 passenger & 0.14 freight
Booz Allen and Hamilton (2005)	**Cost Allocation**	Great Britain	0.19 (renewals as a whole); 0.45 for track renewals	Not tested	3.45
Operations only					
Andersson (2006a)	Econometric	Sweden	0.324	**Falling then increasing**	61 per train-km

(*) average elasticity. - (**) 2005/06 prices

Sources: Wheat (2007) based on Tables 6 and 7 in Lindberg (2006), and updated from Wheat and Smith (forthcoming). The studies highlighted are the latest econometric studies for maintenance and maintenance and renewal costs for each country.

In the case of a Cobb-Douglas model with a constant elasticity less than unity marginal cost must be falling (since marginal cost is less than average cost and so average cost must fall as usage increases, implying that marginal cost has to fall as well to maintain the constant elasticity). When a Translog cost function is estimated, again the elasticity is found to be less than unity and falling with usage. This implies that marginal costs fall even faster with usage than in the constant elasticity formulation. This also seems to be a robust finding across studies which have used a double log specification.

Two exceptions are, firstly, Gaudry and Quinet 2003, who used a generalised Box-Cox model form and found a rising elasticity, and then Wheat and Smith (forthcoming) and Andersson 2006a, who included a third order term for usage. They observed that while the elasticity did initially fall, eventually it began to rise.

3.2 Engineering studies

Two recent proposals attempting to account for the impact of running additional train services on the wear and tear of rail infrastructure are the one currently in use in the UK and a proposal presently being considered in Sweden. These are described in the following sections.

3.2.1 UK ORR's engineering model (Booz Allen Hamilton & TTCI UK 2005)

In the approach used by the ORR the sum of all variable costs estimated using the top-down approach described in the previous section is allocated to different vehicle types by use of a bottom-up engineering model. That is, cost is allocated to vehicles depending on the damage the vehicle does to the network relative to other vehicles. The distribution of costs amongst vehicle types is made according to an Equivalent Gross Tonne Mileage (EGTM) which is a weighting of the actual Gross Tonne Mileage. There are two parts to this weighting, one for damage to track (equation 1) and one for damage to structures (bridges etc., equation 2):

$$EGTM_{track} = K\ Ct\ A^{0.49}\ S^{0.64}\ USM^{0.19}\ GTM \qquad (1)$$

$$EGTM_{struc} = L\ Ct\ A^{3.83}\ S^{1.52}\ GTM \qquad (2)$$

where:	K	is a constant
	Ct	is 0.89 for loco hauled passenger stock and multiple units and 1 for all other vehicles
	S	is the operating speed [mph]
	A	is the axle load [tonnes]
	USM	is the unsprung mass [kg/axle]

GTM is gross tonne miles [Tonne.miles]

These values were derived by fitting regression relationships to a large amount of data from damage models. A number of weaknesses have been identified in this method (ORR 2004):

- As the EGTM calculation is based only on vertical forces, rolling contact fatigue is not accounted for in the distribution to vehicles despite the fact that it is the cause of major maintenance and renewal expenditure (currently 19% of Network Rail's maintenance and renewal budget);
- Rail head wear, axle spacing and wheel profile are also not properly accounted for;
- Varying track quality is not accounted for in the EGTM calculation;
- Vehicle behaviour in worn rather than new conditions is not included;
- Calibration is based on 1999 data.

The ORR commissioned further work on possible improvements to this model and the resulting report by TTCI UK (Tunna 2007) proposes a 'Rail Surface Damage' model with an additional term for Equivalent Vehicle Mileage (EVM) based on the value of 'TGamma' ($T\gamma$)[16] calculated for all the wheels of a vehicle:

$$EVM = J.(f(T\gamma).VM) \quad (3)$$

Where J: is a constant

$f(T\gamma)$ is a function of the contact energy $T\gamma$ at each wheel [N]

T is the tangential force at the wheel [N]

γ is the traction coefficient at the wheel [-]

VM is the miles travelled by the vehicle [miles]

The report proposes a simplified method of establishing the function of $T\gamma$ using a published table of values for a range of curves and cant deficiencies for each vehicle. The proportion of each value for a given route could then be established and the overall EVM calculated.

[16] $T\gamma$ is a measure of the energy dissipated in the contact patch between a wheel and rail.

3.2.2 Proposed methodology for Sweden

Banverket and the Royal Institute of Technology (KTH) (Oberg et al. 2007) have recently proposed a model of track deterioration which aims to produce vehicle related marginal track deterioration costs. The proposed track deterioration model considers four mechanisms:

- Track settlement
- Component fatigue
- Abrasive wear of rails
- Rolling contact fatigue (RCF) of rails

The determining factors behind these mechanisms are 1) the vertical and 2) the lateral wheel-rail forces and the energy dissipation at this interface. A numerical tool (DeCAyS, Deterioration Cost Associated with the Railway Superstructure)) has been developed which includes all four mechanisms. The model used is based on a 'mean value' approach where marginal cost and damage to the track are distributed across the whole network being considered. The model is calibrated to the Banverket system. The DeCAyS tool takes in vehicle and track data and calculates wheel-rail forces. The vertical forces (leading to ballast settlement and component fatigue) are handled separately from the lateral forces (leading to rail wear and RCF).

1) The effect of vertical wheel-rail forces

The total vertical wheel load is evaluated as:

$$Q_{tot} = Q_{st} + Q_{d20Hz} + Q_{dhf} \quad (4)$$

Where: Q_{st} = static vertical load at wheel

Q_{d20Hz} = dynamic vertical load at wheel (up to 20Hz)

Q_{dhf} = dynamic vertical load at wheel (over 20Hz)

The static load Q_{st} includes quasi static forces from curving. The dynamic vertical forces Q_{d20Hz} and Q_{dhf} are calculated from:

$$Q_{d20Hz} = 0.80.K_v.K_s.P.(V+760) \quad (5)$$

$$Q_{dhf} = 1.32\ K_s.V\ \sqrt{m_{uw}} \quad (6)$$

Where: K_v = 0.4 for locomotives and freight wagons and 0.2 for other vehicles

K_s = 0.0036 on high speed track and 0.0042 otherwise

P = static axle load (tonne)

V = vehicle speed (km/hr)

m_{uw}= unsprung mass per wheel (kg)

K_v and K_s are calibrated from measurements of track forces from four vehicles types (including a locomotive, a high speed passenger vehicle and a loaded freight wagon). Track settlement is then calculated using the following equation as proposed by ORE (ORE 1988):

$$E(T_a) - E_0 = k.T_a^{\alpha}.(P_{dyn})^{\beta} \qquad (7)$$

Where: $E(T_a)$ = track deterioration after passage of traffic Ta

E_0 = initial state of track deterioration

T_a = tonnage carried by the track

P_{dyn} = dynamic axle load (kN)

k,α,β = values of coefficients tabulated by ORE.

2) The effect of lateral wheel-rail forces

Only the quasi static component of the wheel-rail forces is required by DeCAyS for calculation of rail wear and RCF. These forces are calculated using the GENSYS vehicle dynamics simulation tool and a matrix of wear numbers is created for each vehicle being considered. A limited number of discrete parameter values for curve radius, primary suspension stiffness, axle load, wheelbase (axle spacing), coefficient of friction and wheel-rail profile combination is included for each vehicle. RCF and wear are then calculated using a modified version of the Rail Surface Damage model (Burstow 2003). When the wear number is between 0 and 15Nm/m no wear or RCF is assumed to occur; between 15Nm/m and 175Nm/m, RCF dominates and above 175Nm/m wear dominates. The total damage for each wheel of a vehicle can then be evaluated from the sum of the three components.

Predicted cost of track deterioration

The combined effect of the various components in the DeCAyS simulation tool predicted for a representative traffic volume and vehicle distribution has been calculated and calibrated based on the known costs for each deterioration mechanism for the year 2001. This is based on the methods used in a previous Banverket tool for prediction of track deterioration cost, DeCoTrack. As a result of this, three weighting coefficients have been established:

K_1 (track settlement) = $7.74.10^{-10}$

K_2 (component fatigue) = $1.08.10^{-9}$

K_{34} (wear and RCF) = $3.98.10^{-2}$

3.2.3 Differences between the UK and the Swedish proposed methods

The methods being proposed for calculation of track access charges in the UK (with the inclusion of the revisions proposed by TTCI) and the DeCAyS method proposed by Banverket are very similar in the models of track deterioration used and the methods of including the vehicle data. Both methods handle vehicle characteristics through tables of wear numbers (or weighted TGamma values) for a limited set of vehicle and track parameters for each vehicle case. These tables are used to establish levels of predicted rail wear and rolling contract fatigue damage. Both methods handle the vertical wheel-rail forces using a simpler calculation based on axle load, vehicle speed and unsprung mass but the Banverket method uses the quasi static force from curving which the UK method does not include. The proposed Banverket method includes an additional model to represent component fatigue at higher frequencies which is not considered in the UK model.

Table 17: Cost variability with traffic by asset type currently in use in the UK

Cost Category	% variable with traffic
Track	
Maintenance	30
Renewals	
Rail	95
Sleepers	25
Ballast	30
Switches and Crossings	25
Structures	10
Signals	
Maintenance	5
Renewals	0
Electrification	
Maintenance	
AC	10
DC	10
Renewals	
AC	35
DC	41
Source: Booz, Allen and Hamilton 2000.	

3.3 Cost-allocation studies

One of the most established top-down accounting models is that used by the UK Office of Rail Regulation (ORR) for assessing the variable access charge the infrastructure manager is allowed to charge. Cost variability proportions are determined by activity category and tables 17 and 18 show those used, respectively, in the 2000 and 2005 reviews of access charges[17]. These proportions are then applied to the total cost by cost category. Variability proportions can be estimated for example using econometric techniques. The ORR approach then uses engineering models for allocating costs to specific types of vehicle.

The studies reviewed seem to indicate that marginal costs are between 0-50% of average costs, however marginal costs vary considerably depending on, amongst others, the cost base adopted, as well as the physical characteristics of the network.

Table 18: Cost variability with traffic by asset type used in the UK ORR's 2005 access charging review

Cost Category			% variability with traffic
Maintenance			
	Track		28%
	Structures		0%
	Signalling		3%
	Electrification		9%
Renewals			
	Track	Plain line	44%
		Switches and crossings	47%
	Structures		3%
	Signalling		4%
	Electrification	AC	11%
		DC	6%
Source: Booz, Allen and Hamilton and TTCI UK 2005.			

3.4 Key outstanding research issues

There have been a number of detailed econometric studies in recent years attempting to quantify the marginal cost of rail traffic covering a wide range of European railways. While

[17] Due to insufficient justification to changes in charges the values from the 2000 review are the ones currently in use.

these have provided fairly consistent estimates of the overall elasticity of maintenance costs with respect to traffic a number of outstanding issues remain:

- Why do estimates of usage elasticity differ so much between countries?
- Why do estimates of marginal costs differ so much between countries?
- Do usage elasticity and marginal cost fall indefinitely with traffic levels or is that result purely due to limitations in model specification and data availability?
- Better usage and elasticity and marginal cost estimates need to be obtained as a function of vehicle characteristics and type of traffic;
- More systematic account needs to be taken of infrastructure characteristics, capability and condition measures;
- Further studies on renewals costs should be carried out.

4 Air transport

4.1 Marginal cost studies

The majority of research analysed for this report are econometric studies and refer to the cost of operating airports. Apart from some early research, they comprise work conducted within the UNITE project for Helsinki airport, two studies performed within the GRACE project for Spanish airports and for a sample of international airports, a British study for UK airports as well as international airports worldwide, an analysis for Swedish airports and available research from overseas (US airports). All these studies employ a firm approach meaning that aggregated cost and performance data for all firms involved in airport services and facilities are accounted for[18]. Furthermore, all studies are based on an econometric analysis of cost data and performance indicators (outputs) but vary regarding the type of cost model estimated. The functional forms used range from Cobb-Douglas cost functions, translog models up to multivariate time series models with correlated error terms for short-run (hourly) labour costs. Apart from studies relating to airport operation we review also one study dealing with the costs of en-route services, and literature on the costs of runway pavement damage.

4.1.1 Studies on the costs of airport operation

Keeler 1970, one of the earliest airport studies, estimated Cobb-Douglas cost functions for capital costs and operating costs, based on pooled time series-cross section data for thirteen US airports for 1965-67. The study found constant returns to scale in airport operations.

Doganis and Thompson 1973, 1974 estimated cost curves for eighteen UK airports for 1969-70 by applying different models to the following cost categories: Total costs, capital costs, maintenance costs, labour costs, administrative costs and operating costs[19]. The empirical basis was derived from questionnaires, direct visits of airports and from financial accounts data. The models were estimated by using a log linear form of the Cobb-Douglas cost functions with work load units (WLU)[20] as output variable.[21] The major finding from

[18] The problem with this is that an airport consists of a large number of different facilities and produces various outputs. Therefore, an "activities" approach would be necessary which calculates the marginal costs for each activity separately. However, this requires detailed and comparable costs data for each activity. In addition, methodological problem might occur if the error terms of the cost functions are correlated. So far, no study has been available which employs an "activities" approach.

[19] Operating costs are made up of maintenance costs, administrative costs and labour costs.

[20] To enable comparisons, a generally accepted definition for Work Load Units (WLU) is that one WLU is equivalent to one passenger and his baggage or 100 kilos of air freight.

Doganis and Thompson (1973, 1974) is the existence of significant economies of scale up to 3 million WLU (for more results see table 19).

Table 19: Model estimates for airport cost categories (Doganis and Thompson 1973)

	WLU[6)]	INT[7)]	DVT[8)]	ATC[9)]	Airports[10)]
Total costs	0.55	34%	69%	71%	18
Capital costs[1)]	0.62	91%	220%		18
Maintenance costs[2)]	0.47	23%	34%	202%	15
Operating costs[3)]	0.54	46%		174%	18
Administrative costs[4)]	0.43			111%	12
Labour costs[5)]	0.58			96%	18

[1)] Capital costs include interest paid on loans outstanding and depreciations for operated ATC facilities. – [2)] In particular the fact of a development programme might mean low maintenance costs because of more up to date capital and equipment. However, low maintenance costs would be associated with a more extensive total level of investment , than at an airport that had not undertaken a development programme. If these two differences are combined then there might be little difference in maintenance costs between airports with development programs and those without. – [3)] Operating costs are total costs minus capital costs. - [4)] Administrative costs constituted internal administration and agency services provided by controlling authorities. – [5)] Labour costs include the expenditure on the work force employed in both ground operation and air traffic control. – [6)] Coefficients of the log linear functional form. – [7)] Indicates how much higher costs of airports with international flights in comparison to those without. – [8)] Indicates how much higher costs of airports with development programmes in comparison to those without. – [9)] Indicates how much higher costs of airports that operate ATC services in comparison to who do not. – [10)] Number of airports for which it has been possible to obtain a value from the questionnaire responses.

Source: Doganis and Thompson 1973, pp. 56-66.

Morrison 1983 estimated a set of cost functions for maintenance, operation and administration, runway construction, land acquisition, capacity rental, and delay expenditures in order to compute optimal long-run toll costs. Morrison's cross-sectional analysis of optimal long-run airport runway fees and investment levels was based on survey data from the ten busiest air carrier airports in the United States for the years 1975 and 1976. For the long-run runway toll revenue function (TR), Morrison (1983) estimated a linear model

$$TR(k, Q_t^i) = p(k) + C(Q_t^1, ..., Q_t^N) \quad (8)$$

where p(k) is the capital rental function and exhibits constant returns to scale, $C(Q_t^I, \ldots, Q_t^N)$ is the total variable cost function reflecting the cost of airport-supplied inputs where t are the time periods over which demand varies, N are the categories of users of the landing area, Q_t^i is the quantity of operations (arrivals, departures, overflights) demanded by user class i (e.g. commercial, general, military and public users) in period t. With the assumed linear cost curve the resulting marginal costs of air carrier operation amount to 12.34 (1976) US$ per ATM.

The studies summarised above were subject to criticism as following:

[21] The models are described in detail in Doganis and Thompson 1973.

1.) Tolofari et al. 1990 argued that all studies which separately estimate an operating and a capital cost model would result in biased parameter estimates because the error terms are likely to be correlated and the separate estimation of the equations fails to adequately model this.
2.) The models in the above papers assume Cobb-Douglas cost functions which imply an elasticity of factor input substitution equal to 1. Such a restriction may result in biased parameter estimates if it is not appropriate (see Main et al. 2003).
3.) Airports do not constantly adjust runway capacity to be optimal for their ATM. If smaller airports operate runways and terminals below capacity, and large airports operate close to or above capacity, then the estimated cost curve may suggest economies of scale when in fact none or at least fewer, exist (Reekie and Crook 1994).
4.) Often, outputs and the costs they gave rise to, do not coincide. For airports, phased capital expenditure may mean that in one year costs are higher or lower than the correct figure. Tolofari et al. 1990 found evidence that this was true for UK airports.
5.) Main et al. 2003 expect that the variance of costs is correlated with airport size leading to the problem of heteroscedasticity.

Tolofari et al. 1990 used pooled cross-section series data for seven airports operated by the British airport authority for 1979-87 (n=49) to model a short run total cost function with fixed capital stock. In a two-step procedure, first the minimising capital value was calculated for each airport and, in a second step, substituted into the short run total variable cost function. A constant which represents the cost of capital was included to give long run total costs. To allow for a flexible functional form, Tolofari et al. 1990 adopted a translog function with the explanatory variables: output (WLU), input prices of labour, equipment, and residual factors, capital stock, passengers per air traffic movement, percentage of international passengers, percentage of terminal capacity used and a time trend. Tolofari et al. 1990 estimated a multi-equation model which included two factor share equations. They found economies of scale up to 20.3 million WLU, indicating a decreasing cost curve.

Main et al. 2003 estimated Cobb-Douglas cost functions for two types of data, a first dataset for 27 UK airports covering the period 1988-89, and a second, international dataset for 44 airports for 1998-2001. Two definitions of operating costs (including and excluding depreciations); and two measures of output (WLU and number of passengers) were used. The models had the form of unrestricted Cobb-Douglas cost functions with the explanatory variables WLU, passengers, passengers divided by ATM, respectively, furthermore the percentage of international passengers, and input prices of staff, other costs and equipment and total assets. Main et al. (2003) found economies of scale up to 5 million WLU (4 million passengers), with a continued but faintly decrease up to 80 million WLU (64 million passengers) (Table 19).

Table 20: Long-run average costs for airports with high passenger volumes in the UK

Number of passengers (millions)	Airport	Predicted long run average cost using 8% of cost of capital[1)]	
		in £ per passenger	€ per passenger[2)]
19.11	Manchester	15.60	17.24
32.24	Gatwick	15.29	16.93
64.67	Heathrow	14.88	16.52

[1)] The underlying assumption of the values in table x is that all airports operate with the optimal amount of capital and that there are no economies of density. - [2)] For the transformation of GBP in Euro the exchange rate from 28.12.2001 was employed.

Source: Main et al. (2003), p. 45; Euro values: own calculations.

Carlsson 2002 estimated short-run marginal airport costs based on cross-sectional time-series data for 19 Swedish airports for 1993-2001 by using a fixed-effects model :

$$C_j = \exp(\alpha_j)\left(Pax_j\right)^{\beta} \tag{9}$$

where C_j is the total costs for passenger services and Pax_j is the number of passengers at airport j. The obtained short-run marginal costs per passenger vary from $ 0.82 up to $ 3.84 with a mean of $ 1.67. Carlssons results imply that the marginal cost for passenger service is approximately 47% of the average cost.

Link et al. 2006 focused on the cost of labour, e.g. one factor input only, and analysed short-run (hourly) operating costs by means of multivariate time series data for Helsinki airport. A SARMA model was specified to identify the relationship between the number of scheduled person-hours in service area and traffic volume

$$\mathrm{Y(t)} = a_0 + a_1 \cdot M(t) + a_2 \cdot A(t) + a_3 \cdot W(t) + a_4 \cdot S(t) + \varepsilon(t) \tag{10}$$

where Y(t) denotes the number of scheduled person-hours in hour t; M stand for the traffic volume measured as aircraft movements; the categorical variable A reflects the influence of additional salaries to be paid for evening and night work; and the dummy variables W and S indicate the influence of weekends and of summer and winter respectively. ε(t) denotes the residuals of the regression model. In order to account for random shocks such as delays, Link et al. 2006 specified models for correlated error terms

$$\varepsilon(t) = \frac{(1 + c_1 \cdot B + c_2 \cdot B^2)}{(1 + d_1 \cdot B + d_2 \cdot B^2) \cdot (1 + d_8 \cdot B^8)} \cdot a(t) \qquad (11)$$

where B is the backshift operator, defined by Ba(t) = a(t - 1), t indicates the time expressed in hours, and a(t) represents the random shocks. While Link et al. 2006 demonstrate that this linear approach has proven to be appropriate for most service areas and for different types of aircraft movements, the relationship between scheduled staff for passenger services[22] and the number of international departing flights (ID) has revealed a non-linear pattern. For this specific case a cubic model

$$\begin{aligned} \mathrm{Y(t)} &= \beta_0 + \beta_1 \cdot \mathrm{ID(t)} + \beta_2 \cdot \mathrm{ID(t)}^2 + \beta_3 \cdot \mathrm{ID(t)}^3 + \beta_4 \cdot \mathrm{A(t)} + \\ &\quad \beta_5 \cdot \mathrm{W(t)} + \beta_6 \cdot \mathrm{S(t)} + \varepsilon(\mathrm{t}) \end{aligned} \qquad (12)$$

again with equation (11) for ε(t) was estimated. The study obtained an average marginal cost estimate for of €22.60 per ATM. However, for international departures this MC ranges between €25 and €72.

The most recent research on marginal costs of airports is summarised in Martin et al. 2006 and covers two case studies conducted within the GRACE project. The first study used data for 37 Spanish airports (n=259) for 1991-1997 which form a symmetric homogenised panel. The second study is based on a pooled database for 1991-2005 of 56 airports in EU, North America, Australia and Asia which has been constructed by Martin et al. 2006. The data has been obtained directly from airport authorities' annual reports and financial statements[23], found either in their websites or at direct request. For both cases, airport services and facilities were divided into essential operational services, traffic handling services and commercial activities. Martin et al. 2006 measured output with three variables: ATM, the number of passengers and the tons of cargo transported in the airport. The input variables were introduced as expenditures and were divided according to the following classification: labour (salaries, employee benefits, full-time equivalent employees), capital costs (amortisation and interest) and materials (terminal surface and runway length). Martin

[22] i.e. check-in and gate services, security, baggage handling, delivery and trolley service

[23] Financial reports previous to the year 97 were collected from the AENA documentation centre.

et. al 2006 used a flexible functional form, a translog long-run mono-product cost function. It is specified in a normalized way using WLUs as output:

$$\ln C_{at} = \begin{array}{l} \alpha_o + \alpha_1 \ln y_{1at} + \sum_{i=1}^{3} \beta_i \ln w_{iat} + \sum_{i=1}^{3} \gamma_i \ln y_1 \ln w_{iat} + \frac{1}{2}\left[\sum_{j=1}^{3}\sum_{h=1}^{3} \beta_{jh} \ln w_{jat} \ln w_{hat} + \rho_1 \ln y_{1at}^2 \right] + \\ + \alpha'_1 \tilde{t} + \sum_{i=1}^{3} \beta'_i \tilde{t} \ln w_{iat} + \gamma'_i \tilde{t} \ln y_1 + \frac{1}{2} \rho'_1 \tilde{t}^2 + \varepsilon_{at} \end{array} \quad (13)$$

where y_1 is the output of each airport measured by its WLU, $\boldsymbol{w}$ is the variable input price vector for capital, labour and materials, t is the time variable, a denotes airports and ε and μ are disturbance terms. Long-run marginal cost estimates were derived including the associated variable input cost share equations:

$$\frac{x_{iat} w_{iat}}{C_{at}} = S_{iat} = \beta_i + \gamma_i \ln y_1 + \sum_{h=1}^{3} \beta_{ih} \ln w_{hat} + \beta'_i \tilde{t} + \mu_{iat} \quad (14)$$

Martin et al. 2006 assume that the disturbance term in (17) has an additive structure:

$$\begin{array}{l} \varepsilon_{at} = u_{at} + v_{at} \\ u_{at} = u_a \xrightarrow{iid} N^+(\mu, \sigma_\mu^2) \quad and \quad \mathrm{v}_{at} \xrightarrow{iid} N(0, \sigma_v^2) \\ u_{at} = \exp\left\{ -\eta(t - T_i \right\} u_a \text{ where } u_a \xrightarrow{iid} N^+(\mu, \sigma_\mu^2) \end{array} \quad (15)$$

where u_{at} is a random disturbance term that captures the possible technical and allocative inefficiency of airports, and the v_{at} is the white noise disturbance term of the model. Martin et al. 2006 estimated an average marginal cost of 8 € per WLU for Spanish Airports and obtained significant economies of scale. For the international sample the short-run marginal cost estimates (€ 4.89 per WLU) are lower than those obtained with the long-run, multi-production specification (€ 5.97 per WLU) or with the long run, mono-production (€ 9.82 € per WLU).

Table 21: Summary of marginal cost estimates for airports

Source	Airports	Type of costs	Time horizon	Functional form	Number of observations	Marginal cost estimates - mean (range in parentheses)	Returns to scale
Martin et al. 2006	37 Spanish airports	total airport costs	long-run	Translog	259	8 € per WLU (0.98€-247€)	increasing
	56 international airports	total airport costs	long-run	Translog, mono-production		9.82 € per WLU	Increasing
			long-run	Translog, multi-production		5.97€/ WLU (0.06€-15€) 406.03 € per ATM (158.74€-2373.61€)	increasing
			short-run	Translog		4.89€/WLU, 119.02€ per ATM	
Morrison 1983	US airports	maintenance, opera-tion, administration	long-run	linear	38	32.97 € per ATM1)	constant
Link et al. 2006	Helsinki airport	labour costs	short-run	linear, SARMA model	336	22.60 € per ATM	constant
		labour costs in pas-senger services area		cubic, ARMA model	336	25€ -72€ per ATM	increasing
Main et al. 2003	British airports	operating costs total costs	short-run long-run	Cobb-Douglas	54	n.a.	increasing
	International airports	operating costs total costs	short-run long-run	Cobb-Douglas	174	n.a.	increasing
Carlsson 2002	19 Swedish airports	total costs	short-run	Log-log model	201	$1.67/PAX ($0.816-$3.843/PAX	increasing
Tolofari et al. 1990	Edinburgh airport	total costs	short-run	Translog	49	Edinburgh: 17€ per WLU, small airport (7 mill. WLU) Glasgow:	increasing
			short-run	Translog	49	Edinburgh: 6.67€/ WLU	increasing
Keeler 1970	US airports	separate models for operating and capital costs	short-run	Cobb-Douglas	26	n.a.	constant
Doganis and Thompson 1973, 74	UK airports		short-run	Cobb-Douglas	18	n.a.	increasing

4.1.2 Studies on the costs for en-route services

Within a fully allocated cost study, conducted by GRA Inc. for the US Federal Aviation Authority (FAA), a marginal cost study for en-route services was performed (see GRA Inc. 1997, Technical Supplement B). The study is based on the FAA's definition of en-route services as "mainly air traffic control services to aircraft operating on instrument flight rule flight plans, flight plans within controlled airspace, principally during the en route phase of the flight" which are provided by Air Route Control Centres (ARCC). Based on data from FAA financial accounts and on activity data for 1995, the study estimates linear cost functions separately for oceanic en-route services which provide procedural control to international flights only and domestic en-route services which provide radar based services. For both, domestic and oceanic en route services, the data did not support variation of incremental costs by user type. The resulting incremental cost shown in table 21 were used by the FAA to determine en route services prices for the fiscal year 1995.

Table 22: En route service incremental cost estimates in the FAA study for U.S. airports

Type of service	Number of observations	Alaskan dummy	Incremental costs (1995 $)	
			Departures	Overflights
Domestic En Route	21	not statistically significant	51.75	25.87
Oceanic En Route	5	20 million	not statistically significant	56.25
Source: FAA AY 1995 Cost Allocation Study, Technical Supplement B.				

4.1.3 Studies on wear& tear costs of runways

While the previous sections were dedicated to studies on the costs of producing airport services and en-route services, this section summarises work on airway pavement damage costs caused by different types of aircraft which was conducted in the US. It is based on measurements performed with the National Airport Pavement Test Facility.

The U.S. Department of Transportation intended to recalibrate the load repetition factors (alpha factors) for four and six-wheel landing gears in the California Bearing Ratio (CBR)-based thickness design procedure for flexible airport pavements. In 1999, the National Airport Pavement Test Facility (NAPTF) was commissioned as a joint venture between the FAA and the Boeing Company. The objective of tests to be done at this facility was to provide additional data for the new thickness design procedures being under development by the FAA. The testing was established with particular reference to the level of pavement damage expected from the six wheel landing gear on the Boeing-777 airplane relative to other landing gears, which are used on aircrafts in the remainder of the fleet. Trafficking on all of the rigid test items was stopped in March 2000 because the rigid test items were deemed of having failed compared to the flexible test items. The criteria used to determine failure of the flexible test items are:

1) one inch upheaval outside the traffic lane;
2) significant structural shear failure in the subgrade or supporting layers; and
3) surface cracking to the point that the pavement is no longer waterproof, signifying complete failure of the surface layer.

The main result was that for the Boeing B-737 (gross weight = 78t) 20 coverages led to pavement failure and for the A 380 (gross weight = 390t) 30 coverages were necessary until pavement failure. More detailed results for the testing of flexible pavements are shown in table 22.

Note, that there are differences in the concepts of “ repetitions to failure” used in table 22 and coverages to pavement failures discussed in the text above. While repetitions to failure indicates the number of times the pavement was loaded by a group of wheels (either six or four in table 22), coverages to pavement failure is the maximum number of times a point on the pavement is passed over (covered) by one of the tires. If the geometry of the gear and the number of tires in tandem are known, a pass-to-coverage ratio can be calculated for an assumed wander distribution. Coverages are used in design, with the first step in the design process being to assume the number of airplane departures and then to divide by the pass-to-coverage ratio to get the number of coverages for design. The use of the coverage concept is an attempt to compensate for the varying geometries used by operating airplanes. For example, full-scale tests may be run with a 747 configuration but the results may be applied to design a pavement for a DC-10.

Table 23: NAPTF flexible pavement tests for 6- and 4-Wheel aircraft configurations

Wheel Configuration	Wheel Load (t)	Repetitions to failure[1)]
Pavement thickness: 47.0 cm		
4-Wheel	20	19000
Pavement thickness: 63.5 cm		
6-Wheel	20	13000
4-Wheel	20	12000
Pavement thickness: 73.7 cm		
6-Wheel	25	90
4-Wheel	25	132
Pavement thickness: 94.0 cm		
6-Wheel	25	1584
4-Wheel	25	2970
Pavement thickness: 119.4 cm		
6-Wheel	30	20000
4-Wheel	30	40000

[1)] Repetitions to failure is the number of times the pavement was loaded by a group of wheels.
Source: Hayhoe, G.F. and Huges, W.J. (2004), p.12.

4.2 Fully allocated cost studies

4.2.1 The GRA cost allocation study for the US Federal Aviation Authority

In 1997, a fully allocated cost study was conducted by GRA[24] Inc. on behalf of the U.S. Federal Aviation Administration (FAA)[25],based on cost and activity data from FAA accounts for the fiscal year 1995. It was intended to provide information for defining the level of user fees and/or aviation taxes, and to identify the share of fixed and variable costs to be allocated to the users of FAA services. Those costs which were suggested to vary with infrastructure use have been allocated to users as proxy for marginal cost prices. The remaining costs were assumed to consist of common and fixed costs and were allocated via Ramsey pricing.

Within a three-step procedure (see Figure 2) i) costs were assigned to FAAs lines of business[26], ii) adjusted in order to reflect that some FAA lines of business produce services

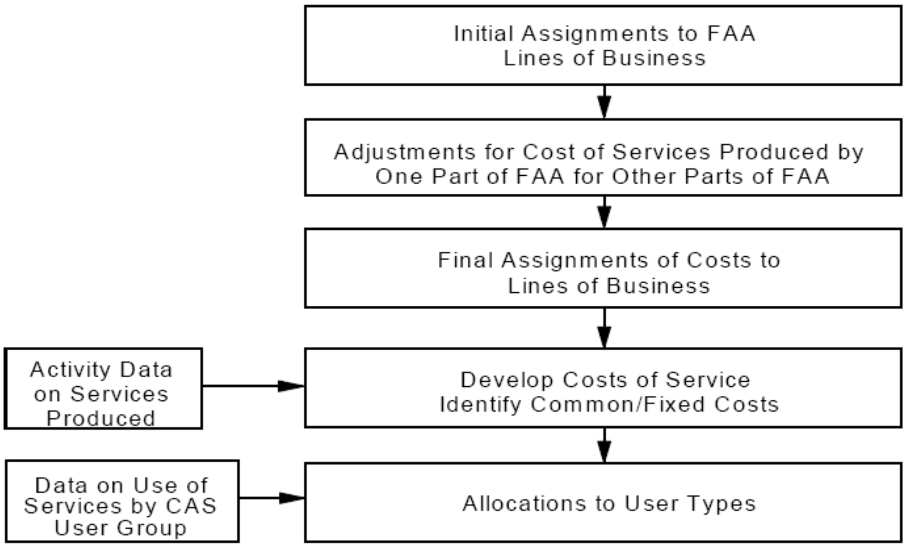
[24] Economic Counsel to the transportation Industry in the U.S.

[25] The FAA is part of the department of transport and is responsible for the safety of the civil aviation in the U.S. FAA's activities major include regulating civil aviation to promote safety, encouraging and developing civil aeronautics, including new aviation technology, developing and operating a system of air traffic control and navigation for both civil and military aircraft, researching and developing the National Airspace System and civil aeronautics, developing and carrying out programs to control aircraft noise and other environmental effects of civil aviation and regulating U.S. commercial space transportation.

[26] Air Traffic Services, Aviation Regulation & Certification, Airport Development, Research & Acquisition, Administration, Office of Commercial Space Transportation.

for other parts of FAA and iii) split up into fixed and variable cost elements by using econometric models and allocated to user types. Non-air traffic service lines of business were treated separately.

Figure 2: Overview of the FAA cost allocation process (Source: GRA Inc. 1997, p. 10)



For air traffic service costs, those components which were identified as direct costs (first column of table 23) were allocated to three broad types of service facility groups[27] (second row of table 23), either based on the financial obligations of each facility or on the share of sector labor or service units provided.

Non-air traffic service costs comprise Aviation Regulation & Certification, Civil Aviation Security, Airport Development and Commercial Space which account for about 27% of FAA's total cost (see table 24).Those cost components which relate to more than a single type of output activity were assigned by a Ramsey pricing procedure. Direct costs were allocated by using activity data.[28] Those direct costs which could not be allocated were classified as common or fixed costs. Approximately 70% of total non-air traffic service costs were directly allocated and are assumed to vary with the amount of service units produced (table 24).

[27] Air traffic service facilities were grouped to reflect their different characteristics.

[28] Non-air traffic lines of business maintain various activity databases. The regulation and certification line of business maintains activity Performance Tracking and Reporting System for Flight Standards, Completed Work Reports for Aircraft Certification, and program activity data maintained by Aviation Medicine.

Table 24: Allocation of direct air traffic service costs to facility groups

Types of direct costs	Shares (%) of direct costs per facility type				
	Air Traffic Route Control Centers		Radar towers and Terminals	Flight Service Stations	All facility types
	Domestic	Oceanic			
Air Traffic Direct	30	26	31	44	31
Airway Facilities Direct	6	7	1	5	8
Airway Facilites En Route	2	0	0	0	1
Flight Inspection	0	0	2	0	1
Medical Field offices	0	0	0	0	0
Direct telecommunications	2	11	1	5	2
Site F&E	25	33	13	4	18
Total share of direct costs	**65**	**77**	**57**	**58**	**61**
Total costs	2595	192	2989	532	6308[1]

Air Traffic Direct Costs, Airway Facilities Direct Costs and Operational Telecommunication Costs were assigned according to the financial obligations of each facility. Airway Facilities Sector Costs were distributed to facilities based on their relative percentages of sector labor. Flight Inspection expenditures are apportioned to the airway facilities based the percentage of inspection hours flown at each inspected facility. The costs of medical field offices at each en route facility were isolated and included as Flight Service Facilities costs for En Route Centers. Facilities and Equipment Costs were assigned to Flight Service Facilities based on the number of end items at each Air Traffic Service Facility. Table sums up the shares of direct costs allocated to each air traffic facility type. [1] total may not add due to rounding.

Source: GRA Inc. 1997, p.80 and calculations by DIW.

Table 25: Directly allocated, fixed and common costs of non-air traffic services - U.S. airports

FAA lines of business	Share (%) in total costs	Cost shares (%) due to GRA analysis	
		directly allocated costs	fixed and common costs
Aviation Regulation & Certification	8.0	33	67
Aircraft certification[1]		18	82
Flight standards		37	63
Civil aviation security	1.3	34	66
Aviation medicine		39	61
Civil aviation security[2]		34	66
Airport development	17.5	89	11
Non-Air traffic services	**26.8**	**70**	**30**

[1] Includes the costs for the national aviation regulation (fixed and common costs) - [2] Incremental costs arise only from passenger transport to assure the safety and security of passengers, crew, baggage and aircraft.

Source: GRA, FAA Cost Allocation Study (1995), pp. 4-5, 13; and calculations by DIW.

Categorisation of user groups

The FAA distinguishes four user groups (commercial users[29], general aviation users[30], public users[31] and overflights[32]) which differ in their usage characteristics of air traffic services. They are further subdivided into subgroups by flight and geographic characteristics (table 25).

Table 26: FAA user groups

User groups	Subgroups	Geographic categories
Air Carrier	- Passenger - Charter - Freight	- International - Overflight - All except international and overflight
Air Taxi	- Passenger - Freight	- International - Overflight - All except international and overflight
Commuter	- Passenger - Charter - Freight	- International - Overflight - All except international and - overflight
General Aviation	- Non-commercial piston engine airplane - Non-commercial turbine engine airplane - Non-commercial rotorcraft - Public aircraft	- Overflight - All except overflight
Military	all	- Overflight - All except overflight
Source: FAA AY 1995 Cost Allocation Study, p.99		

Allocation of direct costs for air traffic services

FAAs motivation to conduct a cost allocation study was to derive marginal cost prices for each user groups. For this purpose a series of cost functions, so-called cost of service models were developed for each facility group.[33] These models have the form of linear regression equations to represent the relationship between costs occurred at individual Air Traffic Service facilities and the outputs provided [34] whereby a set of activity measures such as arrivals, departures, overflights and flight plans & pilot briefs were used to quantify the output of a facility.

[29] Domestic Jet, Charter, All-Cargo, International, Commuter, Air Taxi.

[30] General Aviation Piston, General Aviation Turbine, Rotorcraft.

[31] Military, other public (aircraft operated by the U.S. Government).

[32] Overflights are flights that neither takeoff or land in the U.S., but fly through U.S.-controlled airspace.

[33] Air traffic service facilities were grouped to reflect their different characteristics.

[34] Direct site costs, units of service in terms of activity measures (arrivals, departures, overflights and flight plans and pilot briefs) and categorical variables were used as inputs. To capture the differences in site costs resulting from variations in average pay grades and the higher costs associated with regional facilities dummy variables were included in the models. For more detailed information see Appendix B of GRA Inc. 1997.

Table 27: Output measures and quality indicators of the cost of service models in the FAA study for U.S. airports

Facility Group	Activity Measures				R^2	sample size
	arrivals	departures	overflights	flight plans & pilot briefs		
Domestic en route services	-	X	X	-	0.64	21
Oceanic en route services	-	-	X	-	0.49	5
Radar Towers and Terminals	X	X	X	-	0.61 – 0.83	468
Flight service stations	X	X	X	x	0.92	93

Source: FAA AY 1995 Cost Allocation Study (for further details see Technical Supplement B: ATS Cost of Service Models).

Table 27 shows the estimated shares of incremental and fixed costs for each facility group. The share of incremental cost is remarkably higher for services which are provided at en-route facilities (44%) than at airports (29%) and varies from 14% (oceanic en-route services) to 46% (domestic en-route services).

Table 28: Shares of incremental, fixed and common costs per facility group in the FAA study for U.S. airports

FAA air traffic facility types	Estimated cost shares (%)		
	incremental	fixed	Common
Domestic en route services	46	19	35
Oceanic en route services	14	63	23
Terminals and radar towers	29	28	43
Flight service stations	28	30	42
En-route facilities	44	22	34
Facilities serving at airports	29	28	43
Total Air traffic services	**36**	**25**	**39**
Non-Air traffic services	70	30	
All lines of business	**45**	**55**	

[1] Domestic and oceanic en route facilities [2] Radar towers and terminals and Flight service stations [3] This cost category was not included in the cost of service models.
Source: FAA AY 1995 Cost Allocation Study, p.94 and calculations by DIW.

According to GRA incremental costs are those “costs that change with the level of output produced”[35]. Those non-air traffic service costs, which were directly allocated to users based on activity measure taken from activity databases, were assumed to vary with the level of output produced. Under this assumption, incremental and directly allocated costs are exactly what we consider to be variable costs. Then, altogether 45% of FAA’s total costs are variable and 55% are common or fixed costs.

Allocation of common and fixed costs

FAAs common and fixed costs were allocated to users by using a so-called flights module and a Ramsey pricing module. The flight module was based on detailed aviation activity counts by user types, while the Ramsey pricing optimization module allocated common and fixed costs among users in a way that minimizes the loss in economic surplus while assuring the recovery of all FAA costs. Both tools were employed as follows:

1) Categorisation of all flights which use FAA air traffic services into user groups and into a pre-defined set of distance blocks.
2) Calculation of total operating cost per flight (incl. aviation taxes paid) .
3) Identification of air traffic services used by each flight.
4) Calculation of the incremental cost of air traffic services consumed (with unit costs).
5) Calculation of common and fixed costs as the difference between total air traffic service costs and total incremental costs for all flights.
6) Deriving a representative flight profile for each category and estimating the corresponding demand curve by applying a demand elasticity estimate[36].
7) Optimisation procedure (maximisation of economic surplus under the constraint that total flight costs must cover flight operating costs incl. the cost of FAA services).
8) Calculation of Ramsey prices for air traffic services as the difference between total costs estimated in step 7 and the flight operating costs estimated in step 2.
9) Allocation of common and fixed costs to users so that no users bear common and fixed costs of service it does not use.

4.2.2 Summary of the discussion of FAA practices of cost allocation

HLB Decision Economics Inc. and PricewaterhouseCoopers LLP conducted a study for the UK National Business Aviation Administration which was published in 2004. The study was aimed at proving that Business General Aviation users of FAAs services are overcharged. The study argues that business users of private jets and turbo-props (turbine aircraft) pay $4 million p.a. more in federal aviation user fees than the total costs allocated to this user group.

Table 29: Costs, revenues and cost recovery of General Aviation in fiscal year 2001

[35] GRA (1995), pp. 2-7.

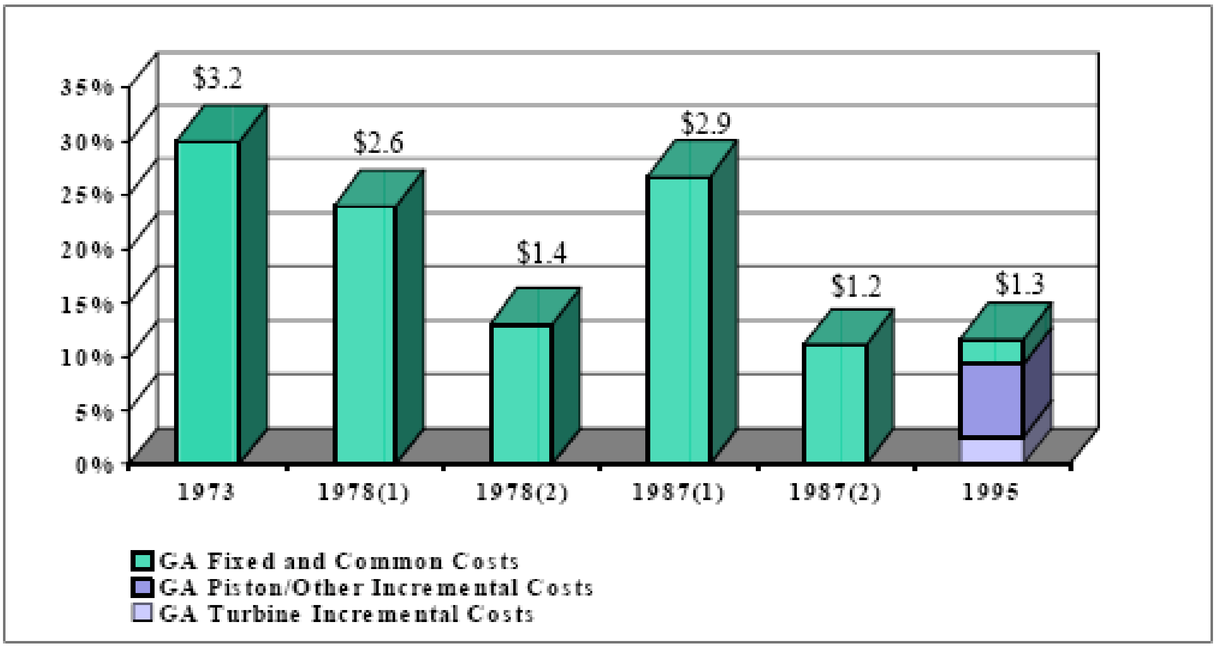
[36] This elasticity estimate is a measure of the likely change in user activity due to overall cost of flying.

Costs, revenues and cost recovery	
Jets and turbo-props tax revenues from jet fuel	$188 million
FAA costs allocated to jets and torbo-props:	$184 million
Cost recovery	
air traffic services	121%
total FAA air traffic and non-air traffic costs	102%
Source: HLB Decision Economics Inc. and PricewaterhouseCoopers LLP 2004, Executive Summary.	

The problem behind the figures given in table 28 is that common and fixed costs are charged to the users of FAA services via a Ramsey pricing procedure, e.g. the amount of common and fixed costs charged to specific user groups depends on their cost elasticity. Due to the high WTP of general aviation users the FAA approach assigns a sizeable amount of common costs to these users[37]. Against this background, HLB Decision Economics Inc. and PricewaterhouseCoopers LLP 2004 have conducted an alternative study on the allocation of FAA costs to the general aviation users. Figure 3 shows the costs allocated to general aviation as a result of several FAA studies. The costs allocated to general aviation range from $1.3 billion up to $3.2 billion due to differences in the definition of recoverable costs and in the methodology of allocating the incremental, fixed and common costs of a joint use system.

[37] FAA did not perform an own study to estimate the demand for aviation services but reviewed more than 25 price elasticity studies. The elasticity estimates ranged from –0.5 to -4.5 with differences being attributed to factors such as trip purpose, fare class, length of trip, passenger income, and geographic characteristics. An average elasticity of –1.0 (-1.5 for general aviation piston aircraft) was chosen for the cost allocation study (see GRA, Inc. 1997, p.108).

Figure 3: Share of general aviation costs from a set of FAA cost allocation studies: An allocation of fiscal year 2001 FAA costs in billions of 2001 Dollars



Source: HLB Decision Economics Inc. and PricewaterhouseCoopers LLP 2004, p. 14.

The FAA studies conducted in 1973, 1978(1) and 1987 used an allocation framework based on marginal cost incurred from the incremental use of FAA services plus a share of common costs allocated in proportion to marginal costs. The FAA study from 1978(2) allocated common costs based on the costs of hypothetical minimum system requirements for general aviation, e.g. the only those costs were attributed which incurred in the use of a general aviation dedicated system. This approach did not charge general aviation for the joint-use system which was developed to serve a commercial aviation industry. The FAA study from 1987(2) allocated only those costs of services which uniquely occasioned by general aviation but no costs of the joint-use of facilities. Fixed and common costs were funded by the public sector. The FAA study conducted in 1995 used an allocation framework based on a marginal cost approach with common and fixed costs allocated based on Ramsey pricing as described above in this chapter).

HLB Decision Economics Inc. and PricewaterhouseCoopers LLP 2004 recommend that FAA's fixed and common costs should be allocated as follows:

1. All common costs associated with Automated Flight Service Stations[38] should be allocated to general aviation users. Of uniquely occasioned costs only a net of assessed and negotiated inefficiency adjustments should be allocated.
2. All common costs associated with other air traffic services should be allocated to commercial users as the current system was designed for commercial users and they are the predominant users of the system.
3. No common costs associated with other FAA lines of business should be allocated to general aviation as these activities are in place to serve commercial users. This is consistent with that employed in the 1995 FAA cost allocation study.

An application of this suggested methodology yields cost estimates for jet and turbo-prop general aircrafts ranging from $169 to $199 million Dollars (FAA fiscal year 2001), e.g. considerably lower amounts than those derived by the FAA studies.

The discussion about the “right” allocation of the share of FAA’s common and fixed costs is still ongoing. For example, GWBAA 2007 states: “Commentaries in not just United’s but also Northwest’s in-flight magazines have singled out business aviation as the cause of flight delays and congestion. In pursuit of airlines’ plan to (1) shift billions of dollars of their costs onto general aviation by introducing new user fees, and (2) shift control of the air traffic control system away from FAA.” Table 29 shows a comparison of FAA’s controversial discussed practices for cost allocation and recovery in comparison to the practices of navigation service providers in other countries.

[38] Automated Flight Service Stations provide pre-flight and in-flight support services. Activities include flight plan filings and amendments, current information on weather and flight conditions and in-flight contacts. They are located at airports and provide support services for aircraft flying up to 6,000 feet high (ground level).

Table 30: Selected air navigation service providers cost recovery practice.

	U.S.	Australia	Canada	EUROCONTROL member states
Uses an aircraft weight factor for terminal charges	x	x	x	x
Uses airport size as factor for terminal charges	x	x		
Uses weight factor for en route charges		x	x	x
Uses distance factor for en route charges	x	x	x	x
Uses congestion pricing	x			
Levies a fuel tax for general and commercial aviation	x			[1]
Charges an annual fee for most general aviation		x	x	[2]
Charges business jets user fees		x	x	x

[1] European Union member states levy fuel taxes for private pleasure flying. [2] Some EUROCONTROL member states charge a flat rate to general aviation aircraft using visual flight rules.

Sources: FAA, Airservices Australia, NAV CANADA, EUROCONTROL.

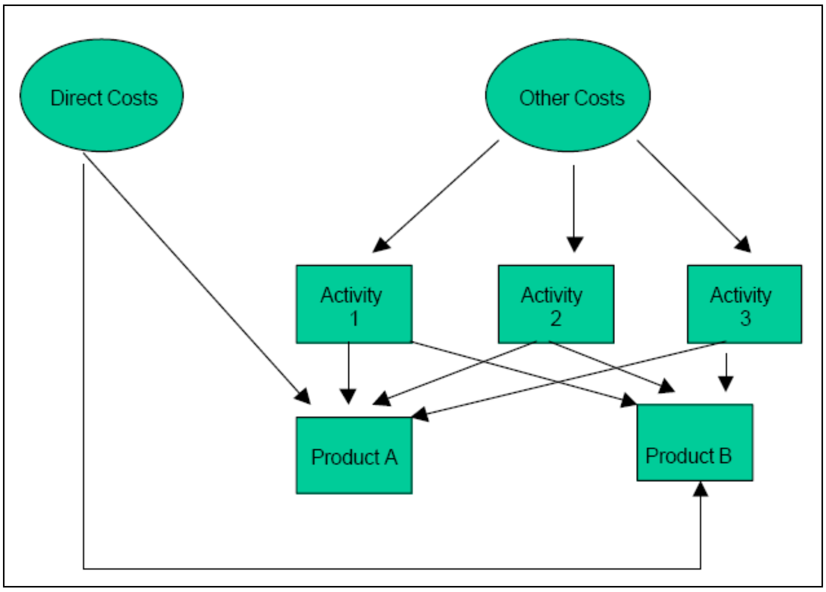
4.2.3 Cost Allocation Report of Europe Economics for the CAA

Europe Economics 2001, a study conducted on behalf of the Civil Aviation Authority (CAA), assesses the cost allocation issues of a possible move to a dual till system of regulation for the UK airports. Manchester Airport and the London airports, which are operated by the British Airports Authority (BAA), are currently regulated under the single till principle. An important issue that affects the feasibility of introducing a dual till system for regulating airports is the allocation of the costs and assets which are used to generate income from activities both within and outside the regulatory till. Different approaches for allocating both joint costs and airport assets are discussed in Section 4 of the report and are briefly summarised here.

4.2.3.1 Approaches suggested by Europe Economics for allocating airport operating costs

There is an important difference between common costs as defined in business accounting systems, and economic joint costs. "Common costs" in the present accounting systems comprise both joint costs and those costs which could through more detailed analysis be allocated to particular activities on the basis of causality. Cost allocation is therefore a two-stage process, with 1) identifying those costs which can be causally attributed to particular services; and 2) allocating joint costs, which will be the remainder.

Figure 4: The Activity-Based Costing system



1. Causally attributable costs: The activity-based Costing Method

Europe Economics 2001 suggests to use the activity-based costing methods (figure 4) which enables to allocate a higher proportion of those costs which are not direct costs in an objective way to outputs. This method requires to report costs for each discrete activity that can be identified within the business. Activities can be thought of as intermediate stages within the production process which contribute to one or more end products or services but do not constitute an end product or service in their own right. All costs within the pool of activities would then be charged to a product/service, depending on the number of "activity units" consumed by that product/service and the rate at which the activity unit is charged. However, even with Activity-Based Costing it will not be possible to allocate all costs to products via activities, and hence the joint costs will remain to be apportioned to outputs.

2. Allocation of joint costs

a) Incremental and stand-alone costs

The boundaries of the costs to be allocated to any service are provided by the incremental cost of that service – the cost that would be avoided were that service not provided[39]; and the stand-alone cost – the cost that would be incurred if that service were provided in isolation. The difference between these two boundaries represents the level of joint costs. With pricing at incremental cost, the service concerned makes no contribution to joint costs; with pricing at standalone cost, the service concerned bears the totality of joint costs. At intermediate prices,

[39] Note, that Europe Economics 2001 obviously uses the terms "incremental costs", "avoidable costs" and "stand-alone costs" synonymously.

the service makes some contribution towards joint costs. The estimation of incremental and standalone costs usually requires the development of hypothetical models of how costs would be structured were joint activities undertaken in isolation of each other. This involves the following questions:

- Should the design of the hypothetical airport be on a "Greenfield" basis or affected by the historical development of the existing airport?
- What mix of traffic is appropriate?
- Should estimates be based on the current or future levels of traffic?
- What level of efficiency should be assumed?

b) Equi-proportionate mark-ups and similar approaches

One mean of allocating joint costs between two areas is through equi-proportionate mark-ups – that is, distributing joint costs in direct proportion to the incremental costs of the two activities. While such an approach may appear to be fair, equi-proportionate mark-ups can be an unduly arbitrary means of allocating common costs and may show no resemblance to what proportion of the joint costs each particular service can bear. Therefore some potentially profitable opportunities, that might be undertaken under a less mechanistic cost allocation, could be foreclosed on account of the burden of joint costs they would have allocated to them. An alternative to equi-proportionate mark-ups would be to use some an alternative ratio between the two activities (e.g. other than incremental costs). For example, in case of some building space, a simple approach could consist in assigning joint cost via the relative floor area occupied by the two activities. Further options could include indicators such as the revenue share of the activities which results from the joint cost facility, or the relative number of staff involved. As with equi-proportionate mark-ups, these approaches are inevitably arbitrary. Nevertheless, they may give reasonable results, and the potential simplicity of such allocation rules could be considered as an advantage.

c) Ramsey-style techniques

The Ramsey pricing rule uses the fact that overall economic welfare can be increased if joint costs are allocated in proportion to the ability and willingness-to-pay of the various parties. This is related to the Ramsey pricing rule.[40] At capacity-constrained airports, demand for

[40] The Ramsey pricing rule implies that to achieve a given level of revenue in the most efficient way, charges should be in inverse proportion to the price elasticity of demand of customers. The implications can be explained intuitively with the following example: if there are two customers, and joint costs are allocated towards the party whose consumption will drop less if the price is increased, then greater output will result if joint costs had been allocated to the more price-sensitive party.

landing and take-off slots is unlikely to be sensitive to price increases at current levels of airport charges. Commercial revenues , by contrast, are normally set at market-clearing levels, and are likely to be relative price-sensitive. This may suggest that joint costs should be allocated to activities within the regulatory till rather than to commercial activities. The resulting increase in airport charges, which were closer to the market-clearing level, would be likely to result in some improvement in the way in which airport slots are used.[41] However, Ramsey pricing is rarely applied in practice in regulated sectors. Apart from other considerations, data availability and quality on the relative price elasticities of different activities are insufficient to enable the allocation of joint costs by Ramsey pricing.

d) Commercial negotiation principle

A further approach is to consider how joint costs would be allocated in a competitive market. Suppose there were two activities, and each would be better off when undertaking an activity jointly rather than separately. In this case, one could thinks of cost allocation as a hypothetical commercial negotiation between the two parties in advance of the expenditure being incurred. This approach would not yield to one single result, since the outcome of a commercial negotiation in these circumstances could be one of a range of possibilities. However, it can safely be assumed that in such a negotiation any profitable outcome would not be rejected. In this sense, this approach resembles a demand-side analysis and could be used for testing the outcome of other cost allocation procedures.

4.2.3.2 Approaches to allocating assets

An important issue in airport cost allocation is the attribution of airport assets to the aviation and the non-aviation business, as well as the choice of valuation approaches for assets. In this section we summarise various approaches outlined in Europe Economics 2001, on the allocation of the aviation asset base, which will in turn affect the capital costs attributed to the aviation sector.

- **Market value approach.** Within this approach the market value of activities outside the aviation sector would be deducted from the current aviation asset base
- **Asset by asset allocation.** An alternative is the allocation of the flotation value to different businesses (aviation, non-aviation) in some proportions arising from accounting

[41] Suggested by the CAA in the December consultation document (paras 3.12-3.17).

data, such as the net asset value. The allocation of asset values between the sectors would then depend on the methodology for valuing assets (historic costs versus current costs)..

- **Opportunity costs.** Another approach is to define the asset base of a specific line of business by applying an opportunity cost valuation to the assets identified in one line of business. However, there are several open issues, as the approach would rely on the valuation of airport land for alternative users.
- **Standalone and incremental costs.** To the extent that an airport can be considered as a joint facility between the services required for air transport and those required for commercial operations, it might be possible to estimate the incremental and standalone costs of assets required by either part of business.

4.3 Open issues

From the currently available evidence the following conclusions can be drawn:

- The majority of studies suggest increasing returns to scale of airport maintenance and operation. This means that the marginal cost curve is non-linear and decreasing.
- Non-linearities are strong for a lower range of WLUs or ATM and rather weak for higher output values.
- Average short-run marginal costs range from 4.89 €/WLU up to 9.82€/WLU for the Spanish airport sample and the international airport sample (Martin et al. 2006). Available estimates per ATM indicate marginal costs between 22.6 €/ATM (Helsinki airport), 32.97 €/ATM (US airports) and 119 €/ATM (international airport sample in Martin et al. 2006).

The studies use different output measures such as air transport movements (ATM), passenger numbers (PAX) and work load units (WLU[42]). This implies first that – in absence of further information - the marginal cost estimates summarised in this section cannot be converted on a unique basis and are hardly comparable. Second, similar to road and rail marginal cost estimates per aircraft type are lacking so far.

[42] One WLU is equivalent to one passenger or 1000kg of cargo (Doganis 1992). For a general discussion of output separation in infrastructure cost studies see Link and Nilsson 2005. An air transport specific discussion can be found in Martin et al. 2006.

4 Waterborne transport

In contrast to other modes of transport there are only few studies on marginal and fully allocated infrastructure costs of waterborne transport. The reason behind is certainly that these types of infrastructure have not been in the interest of charging or taxation policy so far.

We are aware of three studies in this field. The first is an estimation of the costs of maintaining, renewing and operating inland waterways in (West) Germany and a comparison with revenues raised via channel charges (DIW 1990). The study is based on total costs and distinguishes between charged and non-charged waterways but does not provide estimates differentiated by type of vessels. In the UNITE project (Link et al. 2002a,b,c) similar calculations were carried out for all countries as far as data were available and inland waterways play a role for the countries' transport system. However, these estimates are without any disaggregation by vessel types too.

A second source is Van Donselaar and Carmigchelt 2002 which attempts to assess the level of marginal costs at the Rhine river. The result from this study is that marginal costs are negligible. The third source, CE 2004 has analysed the costs of operation, traffic control and maintenance of Dutch inland waterways. They state that only a very limited part of the inland waterway infrastructure costs can be considered marginal because inland waterway infrastructure hardly wears out. Banks are designed to cope with the beating of the waves caused by vessels. Bridges and locks do not wear out faster when they have to be opened more often. Dredging is used rather to remove excess sediment than it is a consequence of shipments. The study concludes that marginal infrastructure costs for inland waterways only occur on the following three points:

- Traffic control (including buoys and signaling);
- Vessels (i.e. patrol vessels and crew);
- Operations (locks and bridges).

The study has estimated the following figures for usage dependent costs:

Traffic control:

Traffic control costs amounted at over €29 million in 2002. CE 2004 assumes that 50% is usage-dependent, resulting in €12 million. Of the remaining costs 80% are made for inland shipping (the other 20% for seaports). These variable costs are divided over recreational and freight vessels according to the share in the total number of ship passages on a (representative) selection of inland waterways. This resulted in variable traffic control costs attributable to freight vessels of €8 million.

Vessels:

Out of a total of €7 million, CE 2004 assumes that these costs are 50% usage-dependent. These variable costs are again divided over recreational and freight vessels according to the share in the total number of ship passages on a (representative) selection of inland waterways. This results in variable costs for 'vessels' attributable to freight vessels of €2 million.

Operational costs:

Operational costs were €50 million in 2002. It was assumed that of this amount 50% is variable. It is hard to estimate the proportion of this amount that is related to transportation of freight, since there is little recreational usage during the more expensive nightly hours and during the winter period. The study has adopted the estimation of the department of the ministry of Transport (DWW) which estimated that 20% of the costs could be attributed to recreational vessels and 80% to freight vessels (€20 million).

Based on the above assumptions, CE (2004) calculated that approximately €29 million could be assigned to freight vessels, which results in an average marginal infrastructure cost of €0.53 per vessel km. Including fixed costs of €300 million in 2002, this results in costs per vessel kilometer of €1.95 - €8.64 depending on the shipment size. An overview of the costs per vessel type is displayed in table 30, in which the marginal infrastructure costs equal the user dependent costs.

Table 31: User dependent and fixed costs for maintenance and repair in the Netherlands in 2002, in €/km (costs in million €)

Vessels type	user dependent	fixed	total costs
inland shipping (loading capacity in tons)			
<250	0.53 (0.2)	1.42 (0.5)	1.95 (0.7)
250-400	0.53 (1.4)	1.95 (5.0)	2.48 (6.4)
400-650	0.53 (3.8)	2.66 (19.0)	3.19 (22.8)
650-1000	0.53 (6.2)	3.73 (43.7)	4.26 (49.9)
1000-1500	0.53 (7.0)	4.18 (55.7)	4.71 (62.7)
1500-2000	0.53 (3.3)	5.20 (32.5)	5.73 (35.8)
2000-3000	0.53 (4.8)	5.58 (50.9)	6.11 (55.7)
>3000	0.53 (2.3)	8.11 (34.9)	8.64 (37.2)
Recreational	0.27 (10.0)	0.51 (18.7)	0.78 (28.7)
(total costs in mln €)	*(39)*	*(261)*	*(300)*

Source: CE 2004, *Onderhoud en beheer van infrastructuur voor goederenvervoer*. Vrije Universiteit Amsterdam, Delft.

5 Conclusions

This deliverable has summarised and analysed available studies on marginal and fully allocated costs of infrastructure maintenance, renewals and operation in the field of road, rail, air and waterborne transport. The aim of this review of available research was to provide a sound basis for the case studies to be conducted within CATRIN. It appears that research varies across modes in terms of types of studies and methodologies used. Marginal cost studies have emerged over the recent years within EU funded projects in particular for road and rail while for aviation a variety of studies on the cost structure of air services, however, not dedicated to estimating marginal infrastructure costs had been performed. Fully allocated cost studies exist traditionally in the road sector where a considerable body of estimation and allocation methods is available, and to a lesser extent in the rail sector and in aviation. The situation is rather poor in waterborne transport.

The review of available research on estimating marginal infrastructure costs and the analysis of methodologies used and quantitative results obtained has revealed a specific problem encountered in all studies. This problem relates to the need of any quantitative studies to have access to comprehensive databases which allow to extract the necessary information in the required level of disaggregation and to apply advanced estimation techniques. However, across modes data availability on the cost of maintaining, operating and renewing transport infrastructure as well as on the use of infrastructure is poor. Most projects in this line of research therefore have to allocate much resources to compile data in a form which allows to draw any conclusions of policy relevance. It is therefore noteworthy that some common conclusions have been emerging from cost studies in different countries.

From the review of national practice and available research we have gained the following insights:

- Bearing the difficulties in obtaining and compiling appropriate databases in mind and given the fact that estimating marginal infrastructure costs has been a relatively young field of research, it can be concluded that research on estimating marginal infrastructure costs has made remarkable progress in understanding marginal costs in different modes. Nevertheless, there remain outstanding issues to be solved.
- One of the most important policy-relevant findings from marginal cost studies is evidence on the degree of cost variability and on the cost elasticity, e.g. the ratio between MC and

AC. For both road and rail, the studies provide evidence that the mean value of the cost elasticity is generally below 1 (road) and 0.5 (rail) respectively. Furthermore, the cost elasticity increases with the time horizon of the measure (for example for road operation: close to zero, for road maintenance: 0.12-0.69, for road renewals: 0.57-0.87, for rail maintenance: 0.07-0.26, for rail maintenance and renewals: 0.18-0.302). Across studies, the variation of the cost elasticity is larger for studies which deal with maintenance costs than for those dealing with other types of infrastructure measures which might hint at problems with defining and quantifying maintenance expenditures.

- At the current frontier of research, marginal cost studies have not yet achieved convergence regarding the shape of the MC curve (decreasing versus increasing). This holds in particular true for the road sector, to some extent also for rail. It appears that for rail the most consistent finding from econometric studies is that i) marginal costs fall with traffic levels, and, ii) are initially very high with low usage levels but fall then sharply. This finding is in contrast to the engineering expectation of a proportional increase of wear & tear with usage.
- For all modes available marginal cost studies obtain "average" marginal cost estimates but fail to provide estimates which are disaggregated by vehicle types or user groups. The MC results are therefore currently not yet in the form needed for pricing policy.
- In air transport, the majority of studies suggest increasing returns to scale of airport maintenance and operation which implies a decreasing marginal cost. Similar to rail, non-linearities are strong for a lower range of usage and rather weak for higher output values. The comparability of results is restricted by the use of different output measures (air transport movements, passenger numbers, work load units) in the studies. Similar to road and rail marginal cost estimates per aircraft type are lacking so far.
- Fully allocated cost studies play a major role in for the road sector. The analysis of allocation procedures used in these studies has shown that there is a considerable variation in the methodologies and allocation factors. Almost all studies split total costs either into fixed and variable costs or into weight-dependent and non-weight dependent costs, an information which can be used as proxy for marginal cost and, in case of weight-dependent costs, as a starting point for allocating marginal costs to vehicle types.
- Further information from fully allocated cost studies are the allocation factors used. The most important factors are the ASSH(T)O factors for allocating weight dependent costs and PCU figures for allocating other types of costs other parts of variable costs but also fixed costs if such an allocation is necessary to meet a budget constraint). The review has

shown that, while in principle the definition and calculation of the ASSH(T)O is straightforward, country-specific differences arise from the different disaggregation of mileage data by vehicle weight classes, the measurements of vehicle loadings, from the distribution of total weight to the axles and from a different reflection of the fact that axle configurations such as tandem or triple axles cause higher road damages than single axles.

- In contrast to the AASH(T)O factors, PCU figures vary between countries not only to different disaggregations of vehicle mileage data in transport statistics but also due to methodological differences. Depending on the underlying concept, PCUs are based on average speed, traffic density, average distance between vehicles within the traffic flow, safety distances and delays. The impact of heavier vehicles on traffic flow is considered by vehicle characteristics such as length and the ratio between weight and engine power on the one hand, and the existence and length of gradients, the share of trucks in the traffic flow, the number of lanes and traffic density on the other hand.

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