Approaches for the calculation of marginal costs of road infrastructure: an updated review

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1. Introduction

According to standard economic theory, short run marginal cost pricing (SRMC) is the benchmark for efficient pricing. In this context, the estimation of marginal costs is of paramount importance to inform decision making on pricing policies and to set investment strategies. At international level, a vast body of literature addressing the estimation of production cost functions of rail companies, airlines or road haulage suppliers is available. However, less attention has been paid to the estimation of costs and cost causation relationships specifically for road infrastructure. This paper aims at bridging this gap by reviewing the methodologies for the estimation of marginal costs of road infrastructure, i.e. the costs incurred by the infrastructure managers for the additional road traffic. We start by introducing the concepts of short run and long run marginal costs as well the efficient pricing principles. Next, we present three different approaches for the measurement of marginal costs of road infrastructure, namely the engineering approach, the econometric approach and the cost allocation approach. In particular, we focus on the specification and estimation of marginal cost functions, on the definition of the explanatory variables of interest and we identify the strengths and limitations of the reviewed empirical applications. The last section addresses concluding remarks and research implications.

2. Short-Run Marginal Cost versus Long-Run Marginal Cost

With respect to the time horizon it is possible to distinguish between short-run and long-run marginal costs. Short–run marginal costs refer to the use of the existing infrastructure. Capacity is given and can not be adjusted to changes of demand in the short- run. The long-run is the time horizon in which all production factors can be adjusted. Therefore, long-run marginal costs include investments in capacity required to accommodate the traffic levels under consideration.

In the specific case of road infrastructure, the short-run is the period in which the capacity can not be changed through the addition of lanes or other measures. Therefore, the short-run marginal cost does not include the costs of land expropriation and construction. For uncongested roads, the short-run marginal cost is equal to the additional damage of infrastructure caused by the passage of an additional vehicle plus non-congestion related externalities imposed on other road users or on the society at large. The short-run marginal infrastructure cost corresponds to the infrastructure cost caused by the passage of an additional vehicle and includes three categories: routine maintenance, periodic maintenance and renewal activities. Routine maintenance is defined to have a very short time horizon and is undertaken to keep the infrastructure open to traffic within the defined quality parameters. This category includes costs concerning vegetation control, removal of organic debris, preservation of road equipment (e.g. safety guardrails), sealing of cracks and patching of potholes. Periodic maintenance refers to two types of measures, namely measures which result in improved texture and smoothness, but does not improve the structural condition of the pavement[1], and measures aiming at enhancing the structural condition of the pavement[2]. Renewal activities have a longer time horizon and are undertaken to bring the infrastructure back to its original condition (Bruzelius 2004). These activities concern not only intervention in the surface course but also on the base and sub-base. The non-congestion related externalities includes the costs of air pollution, global warming, noise emissions, deterioration of nature and landscape, soil and water deterioration and nuclear risks and accidents (van den Bossche, Certan et al. 2001). For congested roads, due to the fact that the additional vehicles "consume" available capacity and inflict additional wear and tear on the road, the costs that they impose on each other became relevant. These specific congestion costs are calculated as a function of extra travel time with reference to the "free flow" travel time. Higher travel time, resulting from lower speed, results in extra vehicle operating costs or even the loss of comfort when driving the vehicle ((Link H., Dodgson et al. 1999) and (Bruzelius 2004))[3].

In the long run, more traffic can be accommodated in the road by investing in increased physical durability or capacity. Therefore, long-run marginal cost includes investments in new road capacity, covering all investments required for the operation of the infrastructure in the long-run. If it is assumed that long run marginal costs refers to the costs allowing for the optimal adjustment of capital stock to the level of output, then congestion costs would be excluded since they would be offset by the extra road capacity provided.

From the perspective of the optimal pricing theory, in the short run, the road user charge should be equal to the short-run marginal infrastructure cost plus the marginal external cost of congestion. The investment in new infrastructure is justified as long as the value of the road user charge exceeds the marginal infrastructure costs for increasing the capacity, since the cost of the additional capacity becomes lower than the existing congestion cost. However, in practice, this mechanism would lead to price fluctuations whenever new investments are made. Therefore, in order to avoid these price fluctuations and since road operators (privately or State owned) are, in principle, more able to estimate future costs of capacity increase than to estimate congestion costs, optimal road pricing is more likely to be based on an average price calculated on the basis of the long-run marginal cost curve,

[1] For instance, resealing is a common pavement maintenance activity to prevent water entering the pavement structure.
[2] For instance, overlays, i.e. adding a thick layer.
[3] Note that the additional costs that the extra vehicle imposes on itself are considered internal. In the case of congestion, which is usually caused by a high number of vehicles, it is extremely difficult to calculate the reciprocal effects. Therefore, as a simplification, if individual internal congestion costs are neglected, external congestion costs are equal to total congestion costs. Link H., J. S. Dodgson, et al. (1999). The Costs of Road Infrastructure and Congestion in Europe. New York, Physica-Verlag.

as shown in the following Picture.

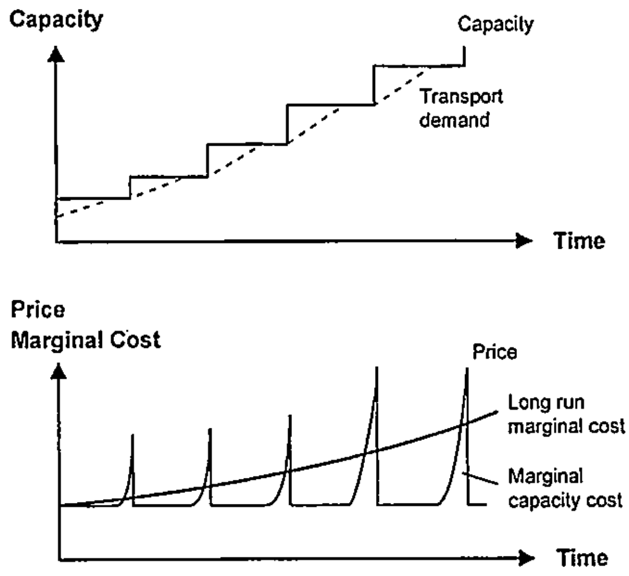

Figure 1 – Capacity increase and marginal cost pricing
Source: (Link H., Dodgson et al. 1999)

As pointed out in Link et al (Link H., Dodgson et al. 1999), charging a price that in advance aims at reflecting the welfare optimum requires two types of information, depending on the pricing approach to be followed (i.e. short-run or long-run). While the short run approach requires information on the congestion cost, indicating the value of the negative effect of a bottleneck, the long run approach requires information about the avoidance costs of the bottleneck, i.e. the investments on additional infrastructure capacity.

In short, if the provision of road space were perfectly divisible and road space always optimally adjusted to the amount of traffic, then short run and long run marginal costs would be equal. As in practice this is not the case, there is a trade off between the advantages of short run marginal cost pricing, which targets the optimal use of current capacity, and the long run marginal cost pricing, which gives appropriate signals about the long term costs of capacity expansion.

In the sections that follow we discuss three different approaches for the measurement of marginal costs of road infrastructure, namely the engineering approach, the econometric approach and the cost allocation approach ((Lindberg 2006), (van den Bossche, Certan et al. 2001) and (Bruzelius 2004)). By doing so we will provide insight on the methods for the calculation of the marginal costs, focusing on the specification and estimation of marginal cost functions as well on the definition of the explanatory variables of interest.

3. The engineering approach

The engineering approach is essentially a bottom-up method[4] consisting in the derivation of physical relationships between infrastructure wear and tear and impact factors (such as traffic volume, climate, etc.) and then assessing these relationships in monetary terms (Link H. and Nilsson 2005). A prominent example of the engineering approach to road infrastructure cost estimation is the AASHO Road Test (Highway Research Board 1961) which sought to define the relationship between road damage and vehicle axle weights and which led to the definition of the so-called 'generalized fourth power law'. This rule indicates that doubling the axle weight increases road damage by a factor of 16. This result implies that road damage is proportional to the number of standard axles passing over it, measured as the ratio of the sum of actual axle weights raised to the power 4 over a given standard axle weight, usually 10 tonnes[5], raised to the power 4. As noted in Link et al (Link, Herry et al. 2002), if road infrastructure costs are assumed to be proportional to road damages then this damage function can be converted into a cost function. However, it is worth mentioning that some studies have demonstrated that there is no convincing evidence that the 4th power rule can be universally applied to allocate structural pavement costs. In fact, different power rules may be appropriate for different types of roads and traffic mix ((Bruzelius 2004), (NERA, AEA Technology Environment et al. 2000), (Small and Winston 1988) and (OECD - Organisation for Economic Co-operation and Development 1988)). For instance, a study carried out by Small, Winston and Evans, concluded that the relevant power varies with the thickness of the pavement (Small, Winston et al. 1989).

In general, the main purpose of engineering based studies is not to estimate marginal costs but rather to provide information to support maintenance and renewal decisions on a disaggregated level. Such information may be expressed in physical terms, (e.g. terminal values for road condition scores or values of assets lifetime) and used together with unit costs or average costs for necessary maintenance and renewal measures per km or m^3 (Link H. and Nilsson 2005). This is not the case in a study carried out by Lindberg (Lindberg 2002) which derives marginal costs of road renewals on Swedish roads, per standard axle and for different road construction profiles and vehicle types. The study uses engineering data to estimate a deterioration elasticity of road surface as well as average costs per renewal measure. The Lindberg study builds upon the 'fundamental theorem of road damage' originally formulated by Newberry ((Newberry 1988), (Newberry 1988) and (Newberry 1989)), which focus on the consequences of road damage and periodic maintenance in the form of overlays. By applying assumptions and engineering experience on the design life of a road, the analytical approach developed by Newberry provides a convenient shortcut, requiring few input data, to large scale experiments, such as the AASHTO road test. In the

[4] In bottom-up methods, the costs of basic packages are firstly considered (e.g. cost for constructing a part of infrastructure for the least demanding vehicle category) and subsequently the additional costs caused by successive vehicles categories are gradually added. Link H. and J.-E. Nilsson (2005). Infrastructure. Measuring the marginal social cost of transport. C. Nash and B. Matthews. Oxford, UK, Elsevier. **14:** 49-83.

[5] ESAL is the acronym for equivalent single axle load. In Europe the standard axle load is assumed to be a 10 tonne single axle with dual tires whereas in the USA is around 8.2 tonnes (18 000 pounds). The estimation of the number of ESALs for a specific pavement is a basic element in pavement design. However, when using this method, there is no guarantee that the assumed heavy vehicles factor is an accurate representation of the heavy vehicles using the road at stake.

Newberry's approach it is assumed that the marginal cost of road damage is equal to the average pavement cost per ESAL.kmand that the so called road damage externality[6] is negligible and therefore can be ignored. The marginal infrastructure cost can be calculated using the following equation:

$$MC = \frac{C \times \varphi}{\Delta T \times Qt}$$

where;

C refers to the cost per km of road overlay,

T is the period between two overlays (expressed in years),

Qt is the annual traffic expressed in ESALs, and,

φ is the share of road deterioration explained by traffic. If this parameter is equal to one, the effect of weather damage is null and marginal cost is just the cost per km of overlay, divided by the total number of ESALs over the entire life of the overlay.

In a nutshell, marginal costs derived with the engineering approach generally reflect maintenance and renewal needs. Cost estimates under this approach generally assume that road managers follow an optimal rule-based behavior in the necessary interventions. For instance once roughness exceeds a certain value the road has to be overlaid (and the corresponding cost incurred). However, this assumption of optimal behavior by road authorities highly questionable, at least in the case of roads directly managed by public sector bodies, since they are likely to be funded by appropriations and subject to weak accountability structures (Bruzelius 2004). As a result, charging schemes based on cost estimates derived under this approach may result in overcharging, when comparing to the real incurred expenditure.

4. The econometric approach

The econometric approach reflects actual or planned spending behavior. However, the costs of infrastructure construction, maintenance, renewal and operation are estimated as a function of a set of determining variables, derived with reference to microeconomic theory. In general terms, this function can be represented as follows:

$$TC = f(Y, Z, P, N, L, K, X, \varepsilon)$$

where TC is the infrastructure cost,

Y is the output of infrastructure provision, generally specified as measures of traffic volume,

Z is a vector of inputs quantities (capital, labor and materials),

P is a vector of input prices (capital, labor and materials),

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[6] In general terms, the road damage externality refers to the cost that an additional vehicle on the traffic flow inflicts on other vehicles due to the respective additional road deterioration.

N is a vector of infrastructure characteristics (e.g. road length and road width),

L is a variable describing the geographical location of the section or network,

K is a vector of variables referring to climate conditions,

X is a vector of any other variables explaining cost variability (e.g., the nature of organisational structure in charge of the operation of the road).

ε is a disturbance term that captures all other non specified factors which may explain the cost variability.

Traffic volume variables, which play a central role in the estimation of such relationship, can be specified using several indicators, such as:

- Vehicle-Kilometers, representing the traffic measured in a given period, usually the Average Annual Daily Traffic (ADDT)[7], multiplied by the length of the road;
- Axle-Kilometers, representing the number of axles multiplied by the length of the road;
- Gross Vehicle Mass (GVM)-Kilometers, whereas the total gross-vehicle mass represents the weight of the vehicle plus its load;
- Per Car Equivalent (PCE)-Kilometers, where PCE stands for an equivalent number of passenger cars that would use the same amount of capacity as a heavy vehicle under prevailing roadway and traffic conditions (U.S. Montana Department of Transportation 2008);
- ESAL-Kilometers, where ESAL stands for Equivalent Single Axle Loads.

A variety of different functional forms, have been used in the literature to specify the general relationship described above[8]. These are mainly linear-in parameters forms[9] ranging from flexible functional forms, such as the translog model, to log-linear models. Link (Link 2006) employs the translog functional form to analyse the cost behaviour of motorways renewal in Germany, based on observed expenditure during a 20-year period. The translog model, which is estimated as a system of equations, has been widely used in applied cost analysis since imposes only few restrictions on the underlying production technology and allows variable elasticities of substitution as well as variable elasticities of cost with respect to outputs.[10]. One of the models estimated by Link

[7] AADT is commonly used but other periods might be used. For instance, the Average Summer Daily Traffic (ASDT) refers to summer traffic only. This measure might be applied in roads where there are significant seasonal traffic volumes.

[8] Specifying a functional form in empirical analysis is equivalent to an assumption that the underlying technologies are wholly consistent with that form.

[9] The Cobb-Douglas, the CES and the quadratic functional models are also linear-in parameters functional forms that are commonly used in applied cost analysis

[10] The most likely contribution of flexible functional forms, such as the Translog, the Minflex Laurent or the generalised Leontief, is that they apparently place far fewer restrictions prior to estimation than the more traditional Cobb-Douglas or CES functional forms (constant elasticity of substitution). However, flexible functional forms are not a panacea for applied production analysis since they also do have limitations. For instance, the degrees of freedom in the estimation are lower than in more traditional forms due to the high number of parameters that are required to be estimated. In addition, since many of the variables might be highly correlated the result is often imprecise parameter estimates. For a detailed discussion on the

establishes the relationship between the renewal costs, the use of infrastructure and factor inputs and prices. The marginal renewal cost per truck-km is derived from the ratio between marginal and average cost per truck-km, which is the main result of the model. The translog functional form used by Link (Link H. and Nilsson 2005) to analyse the impact of traffic volume on renewal costs and to further derive estimates of marginal renewal costs, is presented below:

$$\ln C_i = c + \sum_{j=i}^{m} \alpha_j D_{ij} + \sum_{k=1}^{K} \delta_k M_{ik} + \beta_l \ln p_{li} + \beta_m \ln p_{mi} + \beta_c \ln p_{ci} + \beta_f \ln u_{fi} + \beta_p \ln u_{pi}$$

$$+ \frac{1}{2}\left[\beta_{ll} \ln^2 p_{li} + \beta_{mm} \ln^2 p_{mi} + \beta_{cc} \ln^2 p_{ci} + \beta_{ff} \ln^2 u_{fi} + \beta_{pp} \ln^2 u_{pi}\right] + \beta_{lc} \ln p_{li} \ln p_{ci}$$

$$+ \beta_{lm} \ln p_{li} \ln p_{mi} + \beta_{mc} \ln p_{mi} \ln p_{ci} + \beta_{pf} \ln u_{fi} \ln u_{pi}$$

where C_i represents the renewal costs in section i,

u_{fi} and u_{pi} denote the annual average daily traffic volume (AADT) of trucks (f) and passenger cars (p) in motorway section i,

P´ corresponds to a vector of input prices for labour (pl), material (pm) and capital (pc),

D_{ij} corresponds to a dummy variable indicating the federal state j (j=1,…,m; m=8), and,

M_{ik} is a dummy variable representing the materials used for renewals (k=1,…,K; K=7)

The calculation of marginal renewal costs per truck.km is then carried out by multiplying the cost elasticity (i.e. the ratio between marginal and average costs) by the average cost value per truck.km. This implies that all renewal cost are assumed to be exclusively caused by trucks. The equation for the cost elasticity is presented below:

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

The elasticity is calculated at the mean value of u_p[11].

It should be noted that to circumvent the issue of correlation between passenger car and HGV kilometres, the study uses the ratio between the number of trucks and personal cars[12]. By using that ratio it was possible to cancel the quantitative nature of the regressors and therefore the multicollinearity problem could be solved. However, a negative consequence is that the parameters estimated are difficult to interpret since different roads might get the same ratio even if traffic volumes differ by a large arbitrary factor.

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limitations of flexible functional forms see Chapter 5 of Chambers, R. G. (1988). Applied Production Analysis: a dual approach. New York, Cambridge University Press.

[11] It should be noted that the estimation carried out by Link was not free from problems (a proportion of cost remains unexplained). According to Link these problems might have been overcome with improved data.

[12] As noted by Haraldsson (2006)

Other studies have employed log-linear functional forms to estimate the marginal cost of road infrastructure. The general concept behind these type of studies can be illustrated with the following double log (log-log)[13] functional form (Lindberg 2006)[14]:

$$\ln(C_i) = \alpha + \beta_1 \ln(Q_{Ai}) + \beta_{11} \ln(Q_{Ai})^2 + \beta_2 \ln(Q_{Bi}) + \beta_{21} \ln(Q_{Bi})^2 + \gamma \ln(I_i) + \delta \ln(P_i)$$

where Ci is the cost per annum for section or zone i,

Qi are the outputs for section or zone i, corresponding to traffic for the vehicle classes A and B (a squared term is also included), I_i is a vector of fixed input levels for section or zone I, referring to the infrastructure variables (e.g. pavement type) and P_i is a vector of input prices.

Having succeeded in the estimation of the function presented above, the marginal cost can then be derived as the product of the average cost (AC) and the cost elasticity ϵ. In this example the square of the traffic variable Q_A is included, which means that the elasticity with respect to vehicle type A is non-constant if β_{11} is non-zero.

$$\varepsilon_A = \frac{\partial C}{C} \frac{Q_A}{\partial Q_A} = \frac{\partial \ln C}{\partial \ln Q_A} = \beta_1 + 2\beta_{11} \ln(Q_A)$$

The average cost is simply the cost C divided by the relevant output variable Q[15]. The marginal cost is given by the following equation:

$$MC = \varepsilon AC = \varepsilon \frac{C}{Q_A} = \left[\beta_1 + 2\beta_{11} \ln\left(Q_A\right)\right] \frac{C}{Q_A}$$

A simplified version of the translog functional form, which excludes some quadratic and interaction terms, was used by Haraldsson (Haraldsson 2006) to estimate marginal costs for maintenance and operation of Swedish roads. In this approach factor prices are assumed to be constant across the years and across the operational territorial units of the Swedish Rail Administration that were included in the analysis. The main independent variable of the log linear cost functions estimated is a traffic measure, more specifically, vehicle kilometres. In the case of the operation cost function this variable consisted in the sum of passenger and heavy vehicles traffic. The maintenance cost function only included the heavy vehicles traffic since it was assumed that the need for maintenance is a function of the number of ESALS, which are practically zero for passenger cars (the average number of ESALs for heavy vehicles in Sweden is roughly equal to 1.3).

In the specification of the operation cost function it has been assumed that the need for operation measures[16] in a

[13] In log-log models the parameters are elasticities. In the linear-log model the independent variables are transformed in logarithm, but not the dependent variable. In this model, a 1% increase in the independent variable leads to a x /100 unit change in the dependent variable.
[14] See page 13.
[15] The average cost depends on the traffic volume Q, which is usually expressed as the mean in the sample. However, it should be stressed that, as a rule, the marginal cost varies with the traffic volume.
[16] Operation measures, as defined by the Swedish Rail Administration, are "services to preserve or restore the desired properties of the road system, and which results in effects and economic values of a short-term and immediately active

specific year is independent of the amount of past operations measures, thus excluding the modelling of lagged effects. The specification of the operation cost function for the territorial unit *i* at year *t* is presented below:

$$\ln C_{it} = \alpha + \alpha_i + \alpha_t + \beta_Q \ln Q_{it} + \beta_{Q^2} (\ln Q_{it})^2 + \beta_Z \ln Z_{it} + \varepsilon_{it}$$

where *C* is the cost, α_i and α_t correspond to dummy variables to respectively model territorial unit effects and time effects, Q stands for total vehicle kilometres (heavy vehicles and light passenger vehicles) and *Z* is a vector of road network characteristics (length of roads with different pavement types and extension of different road categories).The model was estimated using a fixed effect panel data estimator. However, it has to be noted that though the author applies a panel data approach to estimate the operation cost function, no details are provided concerning why the homogeneity of the slopes has been assumed neither concerning the potential violation of OLS assumptions (in the presence of non-spherical disturbances GLS estimation would be recommended).

In what regards the specification of the maintenance cost function, though acknowledging that the decision to carry out maintenance activities[17] depends on past maintenance, Haraldsson (Haraldsson 2006) has not used lagged costs as regressors due to data quality issues (extremely detailed data would be required). Instead, Ordinary Least Squares (OLS) regressions on the mean values of the variables over the period of analysis were run in order to cancel out all time related effects. The maintenance cost function has the following form:

$$\ln \overline{C}_i = \alpha + \alpha_r + \beta_Q \ln \overline{Q}_i + \beta_{Q^2} (\ln \overline{Q}_i)^2 + \beta_Z \ln \overline{Z}_i + \varepsilon_i$$

where α_r is a dummy variable for a set of large territorial units[18] $\overline{C}$, $\overline{Q}$ and $\overline{Z}$ are, respectively, the mean values of cost, vehicle kilometres and network characteristics for each territorial unit over the entire period of analysis.

Following the estimation of the cost functions, the marginal costs can be computed by multiplying the cost elasticities by the average costs. The equations applied by Haraldsson to compute marginal costs (Haraldsson 2006) are presented below:

a) Cost elasticity $(\hat{\eta}) = \dfrac{\partial \ln C}{\partial \ln Q} = \hat{\beta}_Q + 2\hat{\beta}_{Q^2} \ln Q$,

b) Average Cost $(AC) = \dfrac{C}{Q}$, and

nature that last for less than one year. These services are in the nature of inspections, rapid rectification of defects that arise suddenly, daily care and the operation of road system equipment". See Appendix 2 of Thomas, F. (2004). Swedish Road Account - Malardalen 1998-2002. Report 500A, VTI.

[17] Maintenance activities, as defined by the Swedish Rail Administration, are "services to preserve or restore the desired properties of the road system and which results in effects and economic values that last for longer than one year". See Appendix 2 of Ibid.

[18] Large territorial units result from the aggregation of the basic territorial units.

c) Marginal Cost $(MC) = \hat{\eta}AC$

Simpler functional forms were used by Herry and Sedlacek (Herry and Sedlacek 2002) and Schreyer et al (Schreyer, Maibach et al. 2002) in order to, respectively, compute marginal cost in Austrian motorways and Swiss motorways and roads. In the Swiss study two types of log-log regression analysis have been carried out. A first one was based on a longitudinal approach of the form

$$\ln C = a + \beta \ln Y$$

where C represents the cost variable, which was tested for different types of costs such as operational maintenance, periodic maintenance and upgrade and renewal costs, and Y stands for the traffic variable, tested for alternative traffic measures such as mileage and gross-tonne kilometers. The second type of regression analysis used cross-sectional data and is based on a similar functional form which also includes a dummy-variable for sections with maintenance expenditures below a certain threshold. In both cases, the general form of the marginal cost function is obtained through a stepwise procedure, consisting in the exponentiation of the functional form:

$$C = e^{(c+\beta \ln Y)} = e^{c} \times e^{\beta \ln Y} = e^{c} \times (e^{\ln Y})^{\beta} = e^{c} \times Y^{\beta}$$

and then in the derivation of the resulting equation:

$$MC = C' = e^{c} \times \beta \times Y^{(\beta-1)}$$

The Austrian study, which is based on a similar functional form, used data on aggregated maintenance and renewal expenditures over a period of 10 years.

Regarding the Swiss and Austrian studies, Link (Link, Herry et al. 2002) points out that the results are not based on observed relationships but rather dependent on certain modelling assumptions, in particular in what concerns the variables gross-tonne km and axle-load km. Therefore, the estimates produced have to be interpreted very cautiously.

Another study in which a log-linear cost function approach was used to estimate the marginal costs of road renewals and maintenance was conducted by Bak et al (Bak, Borkowski et al. 2006). The data used in this analysis covered all national roads in Poland, during a 3 year period (2002-2004). The general functional form specified in the study (all estimated with OLS) is the following:

$$\ln(C) = a + \beta \ln(Q) + \alpha_v + \alpha_r$$

where C refers to the type of cost, Q is the total average annual daily traffic (corresponding to the sum of vehicle kilometers of passenger cars, light good vehicles and heavy good vehicles)[19], α_v is a dummy variable for the

[19] Due to the high correlation between explanatory variables representing different vehicle categories the differentiation between vehicle categories was not modelled.

Polish administrative districts[20] (16 in total) and α_r is a dummy variable for the location of the road section (2 possible locations have been considered, namely, city roads and out of town roads). This functional form was applied to estimate 3 distinct models, which only differ on the specification of the cost variable (C), as shown below:

C_r = average renewal cost per kilometer[21]

C_m = average maintenance cost per kilometer[22]

$C_t = C_r + C_m$

The validation of the results is addressed by comparing the estimates with the results produced in other studies done for German motorways, Swedish roads and the Austrian road network.

The calculation of marginal costs could then be carried out either by using a method analog to the one applied by Haraldsson (Haraldsson 2006) or through the first derivative of each of the 3 cost functions. In the former, the equations applied are the following:

a) Cost elasticity $(\eta) = \dfrac{\partial \ln C}{\partial \ln Q} = \beta_Q$,

b) Average Cost $(AC) = \dfrac{C}{Q}$, and

c) Marginal Cost $(MC) = \eta AC$

The equations resulting from the application of the second method are shown below:

a) $(C_r)^{'} = e^a \times \beta_r (Q)^{\beta_r - 1}$, and

b) $(C_m)^{'} = e^a \times \beta_m (Q)^{\beta_m - 1}$

c) $(C_t)^{'} = e^a \times \beta_t (Q)^{\beta_t - 1}$,

It should be stressed that, as in other studies, the authors refer the influence that data limitations had on the choice of functional form and estimation method, namely:

a) the limited time span (only data for 3 years was available), which did not cover even a single renewal cycle and therefore led to the adoption of an imperfect solution consisting in the scale down of the renewal costs (average renewal costs had to be calculated),

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[20] Designated as "voivodships" in Poland

[21] Corresponding to: (reported renewal cost observed in the year in which it was incurred / average renewal interval, in years, in a given administrative district)/length of the section in km) * 3/ average renewal interval, in years, in a given administrative district.

[22] Corresponding to: maintenance cost in a given section / length of the section in km.

b) the lack of data on factor inputs, factor prices and climate data that hindered the specification of more comprehensive models, and,

c) the lack of data on traffic volumes per axle loads (only traffic data per vehicle type was available), which rendered impossible further disaggregated calculation of marginal costs per type of vehicle (due to collinearity issues).

A modelling approach that allows for the distinction between long run and short marginal road infrastructure expenditures was applied by Levinson and Gillen (Levinson and Gillen 1998). It consists of a Cobb-Douglas functional form (using the log of both dependent and independent variables) estimated using the weighted least squares (WLS) procedure[23]. The functional forms of the long run and short run expenditures functions are as follow:

a) $TE_{LR} = \beta_0 Y_a^{\beta_1} Y_s^{\beta_2} Y_c^{\beta_3} P_k^{\beta_4} P_l^{\beta_5} P_m^{\beta_6} + e$

b) $TE_{SR} = \beta_0 Y_a^{\beta_1} Y_s^{\beta_2} Y_c^{\beta_3} Y_k^{\beta_4} P_l^{\beta_5} P_m^{\beta_6} + e$

where TE_{LR} (the long run total expenditure) is the sum of the annualised capital cost, maintenance expenditure and labour and administration expenditure, the TE_{SR} (the short run total expenditure) is the sum of maintenance and labour and administration expenditure, Y_a is the vehicle miles per year for passenger cars, Y_s is the vehicle miles per year for single unit trucks, Y_c is the vehicle miles per year for combination trucks, P_k is the price of capital (defined as the interest rate paid by the State to borrow money, taking the interest rate borne by the State), P_l is the price of labour (measured by taking the average salary rate of public officers) and P_m is the price of materials[24]. It is worth noting that two other variables describing the characteristics of the road network, namely, the length and width of the road sections, were initially part of the model, to allow the analysis of economies of density[25], but after estimation were dropped from the final model due to collinearity problems. Moreover, the authors mention that other functional forms that allow for the interaction of variables were tested[26], but no satisfactory results were obtained with the available data.

Knowing that the marginal cost can be derived from any twice differential cost function[27], the general equation $MC_i = \frac{TE_x(Y)}{\partial Y_i} = MC_i(Y)$ can be used to compute the long run and short run marginal cost functions for the

[23] The WLS, where the reciprocal of the variance is used as a weight, is used to correct for heterocedasticity in the data.
[24] Bituminous concrete for pavement was assumed to be the main material used in road construction and therefore only its price was used in the study.
[25] In the context of a multi-product cost function, returns to density refers to the relative change in costs to output after an equi-proportional change in all outputs keeping network characteristics unchanged. For a detailed discussion see Oum and Yimin (1997) and Caves, Christensen and Tretheway (1984).
[26] Such as the translog functional form, in which interaction terms allow to capture the relationship between independent variables.
[27] This means that the second derivative of the function exists.

3 vehicle classes *i* [28]. To complete the illustration of the method, the 3 resulting equations for the long run marginal costs are shown below:

$$LRMC_a = \beta_0 \beta_1 Y_a^{1-\beta_1} Y_s^{\beta_2} Y_c^{\beta_3} P_k^{\beta_4} P_l^{\beta_5} P_m^{\beta_6}$$

$$LRMC_s = \beta_0 \beta_1 Y_a^{\beta_1} \beta_2 Y_s^{1-\beta_2} Y_c^{\beta_3} P_k^{\beta_4} P_l^{\beta_5} P_m^{\beta_6}$$

$$LRMC_c = \beta_0 \beta_1 Y_a^{\beta_1} Y_s^{\beta_2} \beta_3 Y_c^{1-\beta_3} P_k^{\beta_4} P_l^{\beta_5} P_m^{\beta_6}$$

The study also includes the calculation of economies of scale and scope. Economies of scale refers to the relative change of cost to output after an equi-proportional change in all outputs and the same proportional change in network size, keeping other characteristics of infrastructure service unchanged ((Oum and Zhang. 1997) and (Caves, Christensen et al. 1984)). In the context of roads, economies of scope show whether it is cheaper to provide a joint infrastructure for light vehicles and heavy vehicles or to provide separate facilities for each. For a detailed discussion on the concept of economies of scope see Panzar and Willig ((Panzar and Willig 1977) and (Panzar and R.D. Willig 1981)) and Baumol (Baumol 1977). For the purpose of the aforementioned calculation Levinson and Gillen firstly calculate the long run and short run incremental costs since they acknowledge that average cost does not uniquely in multi-output technologies (unless the outputs Y are assumed to be equivalent or systemically related). It was found the existence of economies of scale for trucks and diseconomies for cars, which according to the authors, suggests "complementarities in the provision of infrastructure probably explained by the peaked nature of capacity requirements for cars as compared with trucks, which offsets the requirements for thicker pavement. Cars which are used relatively more intensely in the already congested peak period, impose a higher marginal cost than average on infrastructure" (Levinson and Gillen 1998). A detailed presentation of the method used in the calculation of the incremental costs, economies of scale and economies of scope is included in Levinson et al (Levinson, Gillen et al. 1996). It is to be noted that though the study includes the calculation of economies of scale and scope, economies of density could not be investigated. In fact, two variables describing network characteristics, that would have allowed investigating economies of scope[29], had to be excluded from the final models due to collinearity issues.

In short, the review carried out in this section shows that different econometric methods can be applied to compute the marginal costs of road infrastructure. The studies reviewed in this section, as well as some of their strengths and limitations, are summarised in the following Table.

[28] In the general marginal cost expression, *x* represents the type of expenditures function (in the specific case of the study at stake, long run or short run expenditures functions) and Y the output measure (in the specific case of the study at stake, the traffic measure for 3 vehicle classes).
[29] The two variables were road section length and road section width.

Study	Functional Form	Main Focus	Strengths (S) / Limitations (L)
Link (2006)	Translog	Marginal costs of renewals per truck-km, economies of scale	S: Translog is an useful alternative where detailed engineering data is not available L: Interpretation of the results is difficult since a ratio was used to express traffic volumes per vehicle category
Haraldsson (2006)	Log Linear (simplified translog, excluding some quadratic and interaction terms)	Marginal costs of maintenance per truck-km, Marginal costs of operation per vehicle km (no differentiation per vehicle class)	S: Separate models for operation and maintenance costs L: Specification and estimation of the operation cost model (panel data method) could be more detailed
Herry and Sedlacek (2002)	Log Linear	Marginal costs of renewals and maintenance per car-km and truck/bus-km	S: An effort is made to compute marginal cost estimates per vehicle category, though acknowledging correlation between traffic variables L: Simple functional forms have been used due to data limitations, results are not based on observed relationships rather depending on strong modelling assumptions.
Schreyer et al (2002)	Log Linear	Marginal costs of maintenance, renewals and upgrade per car-km and truck.km	S: Marginal cost estimates per vehicle category, though acknowledging that marginal costs derived for specific vehicle categories should be seen as illustrative due to collinearity. L: Simple functional forms have been used due to data limitations, results are not based on observed relationships rather depending on strong modelling assumptions
Bak et al (2006)	Log Linear	Marginal costs of renewals and maintenance per vehicle-km	S: The validation of the results is addressed by comparing the estimates with results from other studies L: Disaggregated calculations of marginal costs per vehicle category was not possible due to data problems

Levinson and Gillen (1998)	Cobb-Douglas	Long run and short run marginal costs for 3 vehicle classes, economies of scale, economies of scope	S: Marginal costs have been computed for 3 vehicles categories, in the short run and long run dimensions (though collinearity between traffic variables may lead to question the parameter estimates) L: Though the study includes the calculation of economies of scale and scope, economies of density could not be computed due to multi-collinearity.

Table 1 – Synthesis of econometric studies reviewed
Source: author

The diversity of functional forms is a consequence of the different objectives and hypothesis defined in the studies, the type of available data and, naturally, of discretionary choices of the authors. In what concerns the specification and estimation of the econometric models, it has been found that collinearity problems detected after the estimation of multi-product output cost functions (or even before, in the analysis of correlation of the candidate variables), which are caused by imperfections in the specification of output measures, led to the use of single output functions. In particular, when axle load information is not available, the specification of the traffic measure is generally done in terms of vehicle kilometers, which can be a problem if the initial objective was to define a multi-product output maintenance cost function. In what concerns the constraints that might arise from data availability, it is noted that when data is only available for a limited period of time, not enough to cover even one single road renewal cycle, data transformations might be necessary[30]. It should also be noted that even when sufficient data is available for a relatively long period of time, allowing for a panel data analysis, the estimation procedure needs to be carefully chosen in order to assure the robustness of the estimator[31]. This is the case in the Haraldsson study (Haraldsson 2006), in which the fixed effect model was preferred over the random effects models on the base of the results of the Haussmans specification test (the assumptions of the random effects estimator were rejected by applying this test).

4. Cost allocation approach

The cost allocation approach is based on fairness principles. In practical terms, cost allocation studies are essentially concerned with the allocation of total costs to road users and with the related issue of achieving a fair solution for the recovery of such costs by way of user charges. Although this approach is not essentially geared towards the calculation of marginal costs, it may be claimed that the cost estimates that are achieved in cost

[30] In the Bak et al (2006) study renewal costs were scaled down and traffic measures scaled up.
[31] A robust estimator can be roughly defined as resistant to error in the results, caused from deviations to model assumptions.

allocation studies could be seen as being relevant to the estimation of marginal costs (Bruzelius 2004). Moreover, since cost allocation studies rely on engineering methods in order to assign the detailed cost components per user class they are useful to gain insight on how to specify marginal cost functions.

Three fairness principles are commonly implicit in cost allocation methods, namely usage-based fairness, causative fairness and intergenerational fairness (ProgTrans AG (Basel) and Institut für Wirtschaftspolitik und Wirtschaftsforschung - Universität Karlsruhe 2007). Usage-based fairness means that the cost referring to the deterioration of certain construction elements (e.g. surface course and drainage) caused by one user class should be borne by that same user class. Causative fairness refers to the fact that the classes of users that are responsible for the costs of dimensioning and provision of certain construction elements should bear the related costs. For instance, the cost allocation method might take into account that it is the heaviest axle load category that determines the dimensions of the road and allocate the cost to the respective user class[32]. Finally, intergenerational fairness means that the costs that a given generation should only be accountable for is just the share of costs that corresponding to the use of the road by that age cohort. It is implicit that future generations should not bear the costs incurred by previous generations.

A common form of cost allocation study departs from a classification of road assets and constructive elements in order to derive the respective total life cycle costs (over a given timeframe). The disaggregated costs are then allocated to the defined users classes on the basis of certain allocation principles using a distribution key. For instance, in a study aiming at updating the cost calculation method that is applied in Germany as a basis to define heavy goods vehicles (HGV) tolls in German trunk roads[33], the cost elements are assigned to user classes according to six allocation principles, which are described below:

- Proportionally allocated costs, linearly by vehicle kilometers (P),
- System specific costs of cars et al (SC),
- System specific costs of goods vehicles, with 3.5 to 12 tonnes Gross Vehicle Weight (SLGV)
- System specific costs of HGVs with 12 tonnes or more Gross Vehicle Weight (SHGV),
- Capacity dependent costs (C), and,
- Weight dependent costs (AASHO),

An overview of the assignment of the cost elements per user class followed in the study, according to the six allocation principles abovementioned, is presented in the following Table.

[32] It is then assumed that traffic and axle load of vehicle classes has little or no influence on road dimensioning.
[33] This toll system is in force in Germany since January 2005.

		Assignment of costs (%) per allocation principle					
Cost categories		P	SC	SLGV	SHGV	C	AASHO
Land acquisition	-					100	
Earthworks/Drainage	B					100	
	M					100	
Base layers	B		X	Y	Z		
	M						
Binders	B						
	M						
Road surface	B					100	
	M						100
Tunnels	B	45			5	50	
	M	80			20		
Bridges	B				15	85	
	M				15	85	
Equipment	B	33				67	
	M	33				67	
Branches, Nodes	B	20	20	10	10	40	
	M	15			10	40	35
Motorway maintenance depots	B	33				67	
	M	33				67	
Service areas and lay-bys	B	20	15	5	60		
	M	20	15	5	60		
Administration/Police	-	33			67		
Upkeep	-	35		15	50		

Table 2 – Cost allocation key of the ProgTrans/IWW 2007 study
Note: ‘B’ stands for building costs whereas ‘M’ stands for maintenance costs
Source: (ProgTrans AG (Basel) and Institut für Wirtschaftspolitik und Wirtschaftsforschung - Universität Karlsruhe 2007)

Due to the high degree of detail in the calculation of costs several allocation keys have been developed to implement the aforementioned allocation principles. For instance, 20% of the construction cost as well as 20% of maintenance cost of service areas and lay-bys is allocated to user classes proportionally to mileage since these facilities are available to and used by all types of users. The remaining costs of service areas and lay-bys are allocated on the basis of the system specific cost of cars, goods vehicles (3.5 to 12 tonnes of gross vehicle weight) and HGVs (gross vehicle weight equal or higher than 12 tonnes) according to the demand for parking spaces. In the case of base layers and binders, the costs are allocated as a system specific cost according to the principle of causation-related incremental costs (X+Y+Z=100). Land acquisition cost, which is considered 100% driven by capacity provision, is allocated on the basis of mileage per user class weighted by equivalency factors which aim to account for the effective roadway space required by each type of vehicle relative to a standard passenger car.

The vehicle equivalency factors of the German study are as follow:

Vehicle Class	Equivalency Values
Motorcycles	0.5
Cars	1
Buses	2.5
Light commercial vehicles (<3.5 tonnes)	1.2
Goods vehicles without trailer	
3.5-12 tonnes	1.5
12-16 tonnes	2.5
16-20 tonnes	3
20-22 tonnes	3
>22 tonnes	3
Rigid and articulated (>3.5 tonnes)	
3.5-12 tonnes	2.5
12-20 tonnes	3
20-28 tonnes	3.5
28-33 tonnes	4
33-40 tonnes	4.5

Table 3 – Equivalency factors for the allocation of capacity-dependent costs in the ProgTrans/IWW 2007 study
Source: (ProgTrans AG (Basel) and Institut für Wirtschaftspolitik und Wirtschaftsforschung - Universität Karlsruhe 2007)

The weight dependent costs are allocated by weighting the mileage by the axle-load specific factors of the AASHO function[34].

In the allocation method applied in a study dedicated to the full allocation of the total annual costs of road infrastructure in the Great Britain (Department for Transport-UK 2000), a set of cost “drivers” is used to allocate each infrastructure cost category to the different vehicle classes, according to a specific formula for each cost category. A synthesis of the allocation principles and cost drivers are presented in the Table below.

Cost Category		Cost allocation driver
Capital charges		15% on basis of maximum gross vehicle weight kms, and 85% on basis of passenger car unit kms
Maintenance costs	Long life pavements	On basis of standard axle kms
	Resurfacing	On basis of standard axle kms
	Overlay	On basis of standard axle kms
	Surface dressing	20% on the basis of vehicle kms, and 80% on basis of average gross vehicle weight kms
	Patching & minor repairs	20% on the basis of average gross vehicle weight kms, and 80% on basis of standard axle kms
	Drainage	100% on basis of vehicle kms
	Bridges & remedial earthworks	100% on basis of average gross vehicle weight kms

34 It is worth mentioning that a 3rd power rule was used instead of the standard 4th power rule derived in the AASHO Road Test

	Footways, cycle tracks & kerbs	50% on the basis of average gross vehicle weight kms, and the other 50% to pedestrians (except on motorways)
	Fences & barriers	33% on the basis of vehicle kms, and 67% on the basis of average gross vehicle weight kms
	Grass & hedge cutting	100% on basis of vehicle kms
	Traffic signs & pedestrian crossings	100% on basis of vehicle kms
	Sweeping & cleaning	50% on basis of vehicle kms, and the other 50% to pedestrians (except on motorways)
	Road markings	10% on the basis of vehicle kms, and 90% on the basis of average gross vehicle weight kms
	Winter maintenance & miscellaneous	100% on the basis of vehicle kms
	Street lighting	50% on basis of vehicle kms, and the other 50% to pedestrians (except on motorways)
Police and traffic warden costs		On the basis of vehicle kms

Table 4– Synthesis of the cost allocation applied in the NERA-DfT UK study
Source: (Department for Transport-UK 2000)

As in the German study, the basic principle consists in identifying any cost component which can be assumed to be incurred by a particular category of vehicle and then to allocate those cost items to the relevant vehicles categories, using a set of cost drivers. The allocation of capital charges, which are calculated by applying a real rate of return of 6% on capital values per kilometer of road (Department for Transport-UK 2000), may indicate that 85% of investment are due to capacity requirements. These capacity costs are allocated in terms of passenger car units (PCUs) which reflect the capacity needs of different vehicle categories[35]. This means that PCUs aim to represent the physical space on the road occupied by the different vehicle classes, with reference to a "standard" passenger car. For instance, goods vehicles have a higher PCU value than passenger cars since they can be expected to impose stronger capacity requirements, as they take up more physical space on the road, they have lower travel speed and require greater acceleration and breaking distances. The remaining 15% capital costs are shared between heavy vehicles (the model includes 33 categories of HGV) according to the kilometers they run weighted by their gross weight (Fowkes, Nash et al. 1990). Maintenance costs are either allocated on the basis of ESAL-kilometers, average gross vehicle weight-kilometers or simply vehicle kilometers.

Cost allocation studies have been also extensively carried out by the US federal and State authorities. The focus of theses studies has been to ensure that the taxes levied on the different vehicle categories correspond to the costs caused by each category. In the cost allocation method followed in a study carried out by the US federal administration (US Department of Transportation - Federal Highway Administration 1997), pavement costs associated with constructing new lanes are split into base facility costs, related to the provision of additional capacity, and incremental (load related) costs required to accommodate the expected axle loadings. Base facility

[35] The PCU is a concept similar to the equivalency factors for the allocation of capacity-dependent costs, used in the German allocation study. The PCU values used in the UK study were not presented in the publicly available documents reviewed.

costs are allocated to different vehicle categories on the basis of vehicle kilometres weighted by the respective passenger car equivalents (PCEs), a measure used to compare the influence of different types of vehicles on highway capacity. A variety of PCE factors were developed for the 1997 federal study, for different roadway configurations and different levels of traffic congestion. Congested PCE factors, referring to traffic during peak periods (i.e. morning and rush periods in urban areas), are used to allocate the common cost share of investments undertaken to add capacity to the highway system. Other example of such method, is the uphill PCE factors, which are used to allocate costs associated with construction or rehabilitation of climbing lanes (Oregon Department of Transportation 2009) .

Cost allocation studies have been widely applied to support policy making although they are often criticized for the substantial level of arbitrariness in the cost allocation process. However, an alternative stream of cost allocation research based on game theory concepts (e.g. Shapley value) has been showing that this problem can be substantially reduced[36].

5. Conclusions and research implications

A standard prescription of transport economics is that, in the short run, the road user charge should be equal to the short-run marginal infrastructure cost plus the marginal external cost of congestion. Other externalities such the costs of air pollution, global warming, noise emissions, deterioration of nature and landscape, soil and water deterioration and nuclear risks may be also reflected in the prices. Moreover, the investment in new infrastructure is justified when the value of the road user charge exceeds the marginal infrastructure costs for increasing the capacity, since the cost of the additional capacity becomes lower than the existing congestion cost. However, since the direct application of this principle would lead to price fluctuations whenever new investments are made and given that road operators are more able to estimate future costs of capacity increase than to estimate congestion costs, optimal road pricing is more likely to be based on an average price calculated on the basis of the long-run marginal cost curve.

Regarding the measurement of road infrastructure marginal costs, it is possible to distinguish between three different types of methods, namely the engineering, the econometric and the cost allocation approaches. Marginal costs estimated on the basis of the engineering approach generally reflect maintenance and renewal needs under the assumption of optimal response behavior by the road managers. However, this assumption of optimal behavior by road authorities is highly questionable, since these bodies are likely to be funded by appropriations and subject to budgetary constraints. Therefore, it can be argued that, under specific conditions, charging schemes based on cost estimates derived under the engineering approach may result in overcharging, when comparing to the real costs incurred.

The econometric approach reflects actual or planned spending behavior and consists in estimating the costs as a

[36] An landmark study in this domain has performed by Doll (Doll 2005)

function of a set of determining variables, derived with reference to microeconomic theory. The review carried out shows that the diversity of functional forms is due to the different objectives and hypothesis addressed in the empirical applications. The issue of collinearity has been found to be potentially troublesome since it may render difficult the calculation of reliable marginal costs disaggregated per type of vehicle. Therefore, one may argue that these methods are of limited use to feed the implementation of differentiated pricing schemes since their output is limited to aggregated marginal costs measures. However, even aggregated estimates can still feed policy making at the strategic level. For instance, long-run marginal cost estimates can be compared with marginal costs of congestion in order to gain insight concerning optimal investment schedules.

The cost allocation approach basically consists in departing from a classification of road assets and constructive elements in order to derive the respective total life cycle costs. The disaggregated costs are then allocated to different users' groups on the basis of certain allocation principles using a distribution key. The main concern is to achieve a fair solution for the recovery of such costs by way of user charges. This approach has been extensively applied to support policy making, most notably, in the US, where cost allocation studies have been carried out to ensure that the taxes levied on the different vehicle categories correspond to the costs caused by each category. Furthermore, these methods are commonly applied to determine the value of road user charges in road concessions, managed under public private partnership schemes. Nevertheless, these studies are often criticized for the substantial level of arbitrariness in the cost allocation process. Taking stock of these remarks, an alternative stream of cost allocation research, based on game theory concepts (e.g. Shapley value), has been demonstrating that this problem can be substantially reduced.

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