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Marginal Costs for Wear and Tear Attributable to Heavy Vehicles Inherent in 'Effektsamband 2000'

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Summary

It is argued that the typically delayed change to the worse for subsequent users of a road, initiated by a passing heavy vehicle, is a function of the damage caused by the strains and stresses from that heavy vehicle and the subsequent maintenance actions taken by the road agency. Therefore, marginal costs caused by the heavy vehicle cannot be assessed without investigating the maintenance strategies used by the road agency. We investigate the functional relationships given in the Swedish National Road Administration's Effektsamband 2000 documents with respect to inherent marginal costs of wear and tear. It is argued in some detail, why the models utilized in the Effektsamband 2000 documents should *not* be used for deriving these marginal costs.

1 Introduction

There are at least two aspects of marginal costs of wear and tear due to heavy vehicles which complicates the determination of these costs. First, an increased deterioration of a road will manifest itself in a change to the worse of the user condition (e.g. increased rutting or unevenness), thus forcing higher costs on subsequent users of the road. However, this change will often not coincide with the time of the passage of the causing vehicle, but instead will be a latent change in the (unobservable) exhaustion of e.g. the road surface, and will become manifest month, years or even decades after that the vehicle passed. Second, adverse changes in the user conditions can be reverted by maintenance actions taken by the road agency. Thus, the costs forced on subsequent users of the road cannot be evaluated without taking the road agency's maintenance strategies into consideration.

The typically delayed change to the worse for subsequent users of the road is a function of the damage caused by the strains and stresses from a heavy vehicle and the subsequent actions taken by the road agency. It would therefore be incorrect to generally attribute the changes to the heavy vehicles alone, at least as long as the road administration is not guaranteed to apply optimal maintenance strategies.

Thus, if the road agency in practice carries out sub-optimal strategies, an amount less than the real marginal costs should be attributed to the additional traffic. This work is not concerned with aspects of *charging* marginal costs, but is only concerned with determining their size. However, it is self-evident that *empirical* field-observations are only available for status quo maintenance strategies. Consequently, one either has to strongly believe that these status quo strategies are close to the optimal ones, or has to acknowledge that the costs resulting from additional traffic are only partly caused by the additional traffic, and that some portion of these costs is caused by the road agency applying sub-optimal maintenance strategies.

In essence, marginal costs resulting from heavy vehicles are only fully attributable to these vehicles if optimal maintenance strategies are applied. Because empirically determined marginal costs combine the costs inevitably caused by the vehicles and the costs which might be avoidable if better maintenance strategies would be applied, empirically determined marginal costs can at their best provide an upper bound for the costs attributable to the heavy vehicles. It seems therefore appropriate to accompany empirical studies of marginal costs due to wear and tear with other sources of relevant knowledge such as results from laboratory research and general engineering reasoning.

The Swedish National Road Administration (SNRA) has a long history of maintaining roads, and has undergone substantial effort to structure the reasoning used for building, improving, and maintaining the Swedish road infrastructure. This work has resulted in a series of publications, here collectively referred to as the Effektsamband 2000 documents. Because these documents are meant to give (among others) the means to conduct cost-benefit analysis for road projects and road maintenance, there must be assumptions about marginal costs present in the documents, at least implicitly. We will here investigate how to determine these implicit marginal costs and will also critically examine the validity of this approach.

The remaining text is organized as follows. Section 2 addresses some of the relevant work concerned with maintenance strategies in general as well as cost-benefit analysis in the context of road depreciation. Section 3 introduces to the Effektsamband 2000 documents. Section 4 investigates the cost-benefit approach to maintenance cycles taken in the Effektsamband 2000 documents and derives the implicit assumptions about marginal costs due to wear and tear in a simple situation.

Section 5 discusses the validity of the analysis in Section 4 and concludes that the Effektsamband 2000 documents cannot be consulted uncritically for the determination of inherent marginal costs. This is a consequence of the fact that many useful models for planning maintenance activities are built on associations between variables, but that derivatives with respect to traffic are only meaningful when the relevant relationships are of causal nature. However, strong association of variables does not imply causality nor does causality imply association of variables. Therefore, models successfully applied to forecasting road user conditions do not necessarily give valid derivations of marginal costs. This point is elaborated upon in Section 5.

Section 6 summarizes the findings and highlights the consequences for the role the Effektsamband 2000 documents play for the determination of marginal costs for wear and tear due to heavy vehicles. The main conclusion is that the value of the Effektsamband 2000 documentation for this particular purpose is that one can get a perception of how the SNRA will react to changes in the user conditions and will adapt its maintenance strategies. It thus serves to access the road agency's intended maintenance activities and therefore helps to provide estimates of upper bounds of marginal costs attributable to the vehicles.

The Effektsamband 2000 documents are intended to be revised on an intermittent basis. While the current documentation is substantial for areas of building and improving roads, the parts concerned with the maintenance and operation of the road infrastructure are less well developed. This is particularly true for long run maintenance strategies, and merely reflects the fact that the body of knowledge is substantially smaller in these areas than in the areas of construction and improvement.

2 Related work

A collection of documents, which is supposed to serve a similar purpose than the parts of the Effektsamband 2000 documents which are concerned with building and maintaining the road infrastructure, is the accompanying documentation of the HDM-III system (Watanatada et al. 1987) and its successor the HDM-4 system (Bennett 1996; Kerali et al. 1998).

General introductions to road engineering are provided by Wright (1996) or Brockenbrough and Boedecker (1996). Huang (1993) deals with engineering aspects of the design of pavements, while Haas et al. (1994) and Shahin (1994) focus on the management of pavements mostly from an engineering perspective. A broader approach including institutional issues is taken by Robinson, Danielson, and Snaith (1998).

Considerations about the value of roads to the users became gradually more important as the funding of road projects became increasingly difficult (OECD 1994). A civil engineering approach which goes under the name of value engineering is described by Tufty (1996), and Morse and Green (1996) describe briefly aspects of life cycle cost analysis for pavements. In Sweden, the feasibility of cost-benefit analysis for road maintenance appears to be studied early by the Swedish Supreme Audit Institution (RRV 1986). Cost-benefit approaches are now undisputed (USDOT 1996; Larsen et al. 2002), and approaches exist which account for the at least partly uncertain nature of road deterioration and maintenance (Tighe 2001). Thomas (1997) provides an overview of stochastic approaches to road maintenance and rehabilitation, and Tack and Chou (2001) are an example of recent work originating from stochastic reasoning.

Pavement maintenance strategies are often assumed to be of the kind where a predetermined maintenance action is carried out whenever a predefined critical value for some deterioration measure is achieved. While it is true that there are situations where such a maintenance policy is optimal (Li and Madanat 2002) this is not a characteristic of optimal solutions in general. There is a wide variety of approaches how to maintain deteriorating systems in general (Wang 2002), and the problem of optimal pavement maintenance has received much attention (Carnahan et al. 1987; Carnahan 1988; Durango and Madanat 2002; Madanat and Ben-Akiva 1992). Still, the assumption of a single maintenance action being carried out periodically whenever a particular level of deterioration is reached is evidently the most common one when marginal costs are to be assessed empirically.

Small, Winston, and Evans (1989) have pioneered the empirical assessment of marginal costs due to wear and tear. Recent efforts to estimate marginal costs include Jara-Díaz, Donoso, and Araneda (1992) and Ozbay, Bartin, and Berechman (2001).

Link (2002) estimates the average renewal costs for German motorways applying essentially a multiple linear regression model which relates renewal expenditures to traffic and some other variables. The resulting model has the ratio of average annual daily traffic (AADT) for trucks to AADT passenger cars as its central explanatory variable. Consequently, Link derives the marginal costs with respect to this ratio. It can only be speculated in why this ratio outperforms the variables AADT trucks or AADT passenger cars alone as explanatory variable for road deterioration. Be that as it may, the resulting model in which the total amount of traffic is not important is counter-intuitive and questions the validity of this particular modelling approach.

Lindberg (2002) elaborates along the lines of Small et al. (1989) and estimates the marginal costs of road maintenance (agency costs only) for heavy goods vehicles on Swedish roads. Besides numerical values for the marginal costs, Lindberg finds some relationships between marginal and average costs which might be of value for the implementation of marginal cost pricing.

Lindberg uses data from the Swedish long term pavement performance (LTPP) program. The in-service road sections monitored in this program are *not* representative for all roads in Sweden, but have been selected purposely to be mostly of the kind where traffic volumes are low enough in order to reach the stage where fatigue cracking of the pavement can be observed (Göransson and Wågberg 2002, p. 7). The deterioration measure which triggers a predetermined maintenance action is taken by Lindberg to be an index for cracking, and the functional relationship between the extend of cracking and traffic load is based on the work by Wågberg (2001).

However, in Sweden cracking is *not* the factor that traditionally triggers a maintenance action, but instead roads are maintained because of extensive rutting, often caused by passenger cars with studded tires. Nevertheless, attention has been drawn to the fact that cracking is an increasing problem in Sweden, presumably the result of the application of wear-resistent pavements in combination with modern studded tires that are less harmful to these pavements, and therefore allow pavements to be in service longer.

In any case, the fact that the data used by Lindberg is (largely) collected on a subset of the Swedish road network which is known to be maintained for 'untypical reasons' questions the relevance of the study for 'normal' Swedish roads. Also, it should be kept in mind that the criterion that triggers maintenance in Lindberg's study is not the relevant one for Swedish roads in general.

3 The Effektsamband 2000 documents

3.1 The collection of documents

The documents collectively referred to as Effektsamband 2000 documents (SNRA 2001a) are meant to be one of the SNRA's cornerstones for planning, projecting, and evaluating all kinds of measures related to the Swedish road infrastructure. For a summary of these documents see SNRA (2001i).

The preliminaries and some for all relevant enterprises common concepts are described in SNRA (2001d). Two volumes are dealing with questions regarding maintenance and operation of the road infrastructure, namely SNRA (2001b) outlining the applied concepts and defining relationships, and SNRA (2001c) guiding through the use of the former document and exemplifying its useage.

Three volumes are dedicated to new constructions and more substantial improvements of the existing road-related constructions. The core volume is SNRA (2001f), accompanied by a volume guiding through its usage (SNRA 2001h) and a collection of examples (SNRA 2001g).

One volume is devoted to aspects of mass transportation (SNRA 2001e), and one to the SNRA's exercise of public authority (SNRA 2001j). All documents are provided on a CD (SNRA 2001k), which also contains a computer program facilitating the assessment of actions and their consequences. The use of this tool is described in SNRA (2001l).

3.2 Purpose and intended use

The Effektsamband 2000 documents are intended to be used for a systematic evaluation of road infrastructure improvements as well as for the evaluation of maintenance and operation of the infrastructure including road signs and the like. Some effects are described only verbally and a particular project's impact on these criteria is to be judged on an ordinal scale. Other effects are evaluated on a ratio scale (essentially monetary values) through functional relationships. These relationships stem from a wide variety of research activities.

It is to be understood clearly that Effektsamband 2000 is meant to summarize research results and makes them operational for the purpose of road infrastructure planning. It is therefore almost self-evident that Effektsamband 2000 has to rely on relationships that sometimes are less well founded. Effektsamband 2000 is meant to be authoritative in the planning process within the SNRA, but not to be authoritative in the sense that cutting edge knowledge is used for all the implemented relationships. Consequently, the SNRA intends to revise the Effektsamband documents on an intermittent basis, but to keep the content unchanged in-between and to make explicit in the evaluation of potential projects which version of the Effektsamband documents has been used.

As already mentioned, the Effektsamband 2000 documents are intended to be used for evaluation of infrastructure planning. A typical usage would be to compare the status quo solution of e.g. a particular section of a rural road with a limited number of alternative solutions in order to decide upon those potential improvements' merits and in order to conduct a cost-benefit analysis for those portion of the effects which are evaluated on a common ratio scale (monetary evaluation). The functional relationships entering the cost-benefit analysis will typically have some measure of traffic volume as one of their arguments. For a given well defined situation it is therefore technically feasible to calculate the partial derivative with respect to the measure of traffic volume, i.e. to determine the marginal costs with respect to changes in traffic volume which are implicit in the employed functional relationships. However, technical feasibility does not mean that the approach is meaningful, something which is addressed in Section 5 below.

3.3 Difference to prior documents

The Effektsamband 2000 documents are not simply updates of older documents such as SNRA (1989). Instead, a different approach to the results of maintenance actions is used. In prior documents, particular maintenance actions tended to be associated with various effects in a more or less unconditional way. The Effektsamband 2000 documents make this reasoning more explicit in that they relate a maintenance action to a change in the condition relevant for the road user. This condition is then evaluated and—if possible—a relationship is provided which links these conditions to effects. As an example, repaving was linked to a change in the frequency of traffic accidents and vehicle costs, directly depending on the chosen type of pavement (SNRA 1989, p. 62). In the Effektsamband 2000 documents, repaving has an effect on rutting and unevenness, and these features have in turn an impact on the frequency of traffic accidents and vehicle costs.

This is an important change for the evaluation of maintenance actions as well as the incorporation of new insights provided by scientific studies. One aspect of this approach is that if a maintenance action fails to provide a certain user condition it will not be considered to have the envisaged effect either. E.g. can milling and repaving, where the old pavement is mixed in-situ, fail to provide a remedy to pronounced rutting.[1] In such a case, the maintenance action will not be considered to have changed rutting-related user costs.

The view in the Effektsamband 2000 documents focuses on the scope of providing certain conditions for road users and is not limited in that only well known maintenance actions are described. Any maintenance action that will change the user condition in the same way will have the same effect on user costs.

[1]If the rutting is the result of plastic deformation of some pavement layer due to inadequate material quality, pronounced ruts might occur again shortly after reopening for traffic, simply because the faulty material is reused when in-situ mixing is applied.

3.4 Level of details

The level of detail in the Effektsamband 2000 documents is largest for new constructions, which are described in terms of travel time, accident risk, fuel consumption etc. These constructions include motorways (freeways), four-lane rural roads, expressways without opposing traffic (expressroads), rural roads without opposing traffic, normal rural roads (6.5 - 11 m wide) and narrow rural roads (less than 6.5 m wide).

For the economical assessment of projects, some costs are only approximately described, e.g. accessibility for disabled persons or esthetical aspects of some structures. Among those costs where explicit guidelines are provided are travel time* (for persons and goods), traffic safety*, emission/pollution* (CO_2 emission, but also combustion gases and the like), noise, barrier costs, vehicle costs*, and operation and maintenance costs*. The asterisked entries are implemented in the computer program EVA 2.31 and are therein used to evaluate differences between the status quo solution of a road and alternatives.

An evaluation of a project is carried out by essentially conducting a cost-benefit study based on the subgroup of effects which is expressed in monetary terms. In addition to that a description of the relevance and possible direction of the benefits for the effects not described in monetary terms is provided.

4 Marginal present-cost change for total pavement maintenance and user costs

4.1 Outline of problem

Throughout we focus on the problem where a maintenance action such as resurfacing is carried out periodically. The situation where essentially the same maintenance measure is carried out repeatedly has received much attention (Li and Madanat 2002). Anyhow, more elaborate sequences of minor and major maintenance actions are of practical interest and the Effektsamband 2000 documents do present some details even for their analysis. The nature of the analysis gets more complex and in order to get some principle insights to marginal cost assumptions implicit in Effektsamband 2000, we will deliberately restrict ourselves to the most basic situation.

The principle idea is depicted in Figure 1, which presumably draws upon a situation which can be adequately described in a continuous time frame with continuous state space and deterministic pavement deterioration (even though this is not formulated explicitly in the Effektsamband 2000 documents).

The present costs (N) of the total pavement maintenance and user costs are to be calculated as (SNRA 2001c, p. 38)

$$N^* = \frac{365\,Q \cdot K_T(L) \cdot (1 - e^{-rm}) \cdot S + K_V \cdot \left(1 - e^{-r(m-L)}\right) \cdot e^{-rL}}{1 - e^{-rL}}, \qquad (1)$$

where

Q	:	average annual daily traffic, AADT (vehicles/day)
S	:	length of the section (km)
$K_T(L)$	:	present value at year T for the total user costs per user and km between T and $T + L$
K_V	:	maintenance costs (for the agency) per km in SEK for each maintenance instance
r	:	social discount rate
m	:	time horizon for analysis in years after year T

The user costs consist of increased accident costs, vehicle costs, and costs for comfort and travel time. Costs for users from delays due to road works or other temporary congestions are—to the best of the author's knowledge—not included in the guidelines of the Effektsamband 2000 documents.

Observe that $K_T(L)$ is a function of L, the time span between successive pavement rehabilitations. This time span may or may not depend on Q. In well specified models, optimal cycle length can be derived from theoretical considerations. However, studies with the purpose to determine maintenance intervals have not been carried out in Sweden (SNRA 2001b, p. 42).

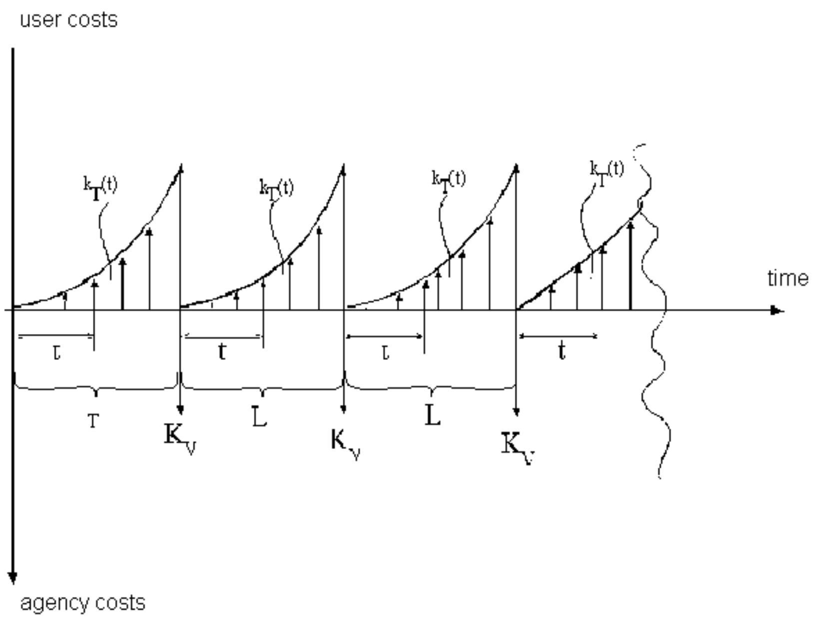

Figure 1: *The principle situation for a periodically applied maintenance action such as resurfacing. After the maintenance measure is applied, the user condition is set back to a more favorable state. As a consequence, the user costs are lower after the maintenance action but increase gradually as the road deteriorates. At a well specified point the same maintenance action is carried out again. The maintenance costs are periodical expenditures by the agency, while the user costs are constantly present but to various degrees. Source: SNRA (2001c, p. 38, customized).*

4.2 Cycle length independent of Q

If the cycle length is independent of Q, the first derivative of N^* (agency and user costs) with respect to Q is given by

$$\frac{\partial N^*}{\partial Q} = \frac{365 \cdot K_T(L) \cdot (1 - e^{-rm}) \cdot S}{1 - e^{-rL}} \,. \tag{2}$$

Note that this is the derivative with respect to AADT, and not with respect to a single vehicle. In this equation, S is easily obtained from road inventory data and L is externally determined. Not surprisingly, because the length of the maintenance cycle L is assumed to be unchanged by the change in traffic, the marginal N^* is independent of the agency costs K_V. A thorough study of SNRA (2001c, Ch. 4) reveals that the present value of the total user costs, $K_T(L)$, is suggested to be a function of rutting and unevenness as expressed by the International Roughness Index (IRI). Both of these criteria are modelled as developing over time, where time is the only explanatory variable. $K_T(L)$ does depend on the proportion of heavy vehicles, but does so only because different values for travel time and comfort as well as vehicle costs are used for passenger cars and heavy vehicles (SNRA 2001c, App. 1). Following these specifications, unevenness and rutting are not changed by the change in traffic, and the change in N^* is merely the change due to the vehicles in addition or subtraction to the status quo traffic.

Note that the right hand side of Equation (2) is always non-negative, meaning that N^* is increasing with additional traffic. Furthermore, from the fact that the cycle length, agency costs, and progress of rutting and IRI are unrelated to the change in traffic, the additional present costs are entirely attributable to the costs for the additional users (at least as long as other users' accident risk remains unchanged). In this situation, the marginal costs for the road user are exactly the costs taken by the very same user in terms of travel time and comfort as well as vehicle costs. Such a user does not create additional costs for other users and does not create costs for the agency.

4.3 Cycle length depends on Q

Suppose know that the cycle length L is a function of the amount of traffic Q. To highlight this fact, we can rewrite Equation (1) as

$$\begin{aligned} N^* \;=\; & \big[365\, Q \cdot K_T(L(Q)) \cdot \left(1 - e^{-rm}\right) \cdot S \\ & + K_V \cdot \left(1 - e^{-r(m - L(Q))}\right) \cdot e^{-rL(Q)}\big] / \left(1 - e^{-rL(Q)}\right) \,, \end{aligned} \tag{3}$$

where the derivative with respect to Q might be evaluated numerically for any given situation. Even in this model the maintenance costs per maintenance instance, K_V, are constant over time, but now the cycle length will change with the change in traffic.

Following SNRA (2001c, p. 42), the optimal maintenance cycle $L^*(Q)$ can be determined by an iterative algorithm. Even the discounted total user costs will change due to the change in cycle length. However, very little is found in

Effektsamband 2000 which provides guidelines on the development of rutting and longitudinal unevenness as a function of traffic. The in SNRA (2001c) specified functions relate these user conditions to time with the consequence that the derivative with respect to traffic volume is zero, meaning that conditions for subsequent users are unchanged by additional traffic. This aspect is discussed in Section 5 below.

Furthermore, Equations (1) and (3) are built upon the concept of AADT (Q) as a measure for traffic volume. Therefore, the marginal effects of additional passenger cars will be formally identical to the marginal effects of heavy vehicles, unless the user costs are a function of the proportion of heavy vehicles, which of course changes if a vehicle of a particular kind adds to the traffic.

4.4 Numerical example

This example is derived from the setting in Example 1 in SNRA (2001c, Sec. 4.5). Under consideration is one kilometer of the right lane of a motorway with two lanes, which carries an AADT of 10 000 of which 4 000 use the right lane. Rutting is linearly increasing with 1.0 mm/year. After repaving, the rut depth is set back to 2.0 mm. The right lane is 4 meter wide and the maintenance action (repaving) costs 65 SEK (7 EURO) per square meter. The social discount rate is 4%.

Following the instructions given in SNRA (2001c), the optimal cycle length is determined to be 11 years. Furthermore, the user costs needed in Equation (1) and (2) above is calculated with the help of an appendix and partially based on a computer program only referred to in SNRA (2001c). These costs evaluate numerically to $K_T(L) = 0.04481758$, and are meant to include accident costs, vehicle operating costs, and comfort costs. The agency costs evaluate to $K_V = 4\text{m}\times 1\,000\text{m}\times 65\text{SEK/m}^2 = 260\,000$ SEK (28 400 EUR).

With the remaining values $Q = 4\,000$, $S = 1.0$, and $L = 11$, Equation (1) and Equation (2) give the present costs of this maintenance strategy and marginal costs depending on the time horizon after the first maintenance action, m.

Table 1 summarizes the costs for a number of different analysis horizons. N^* denotes the present costs as derived from Equation (1), whereas MC_{AADT} gives the marginal costs as derived by Equation (2). However, a change in AADT means one additional vehicle per day on the average. Therefore, one single vehicle may be represented by a change of 1/365th of AADT. The resulting marginal cost is denoted by $\text{MC}_{\text{veh.}}$ and given for a trip of 100 km length on a similar road. (The other costs are given for the project length of one kilometer.)

Figure 2 shows the dependence of the marginal costs on the planning horizon. The commonly used planning horizons of 40 to 60 years are highlighted in the graph. The marginal costs as expressed for one vehicle during a 100 km long trip on a similar road varies from 10 to 11.5 SEK (1.1 to 1.25 EUR) as the time horizon for the analysis varies from 40 to 60 years.

	40 years	50 years	60 years	70 years	80 years	∞ years
N^*	469 652	530 505	571 295	598 638	616 967	654 233
$\mathrm{MC}_{\mathrm{AADT}}$	36.68	39.74	41.79	43.16	44.08	45.96
$\mathrm{MC}_{\mathrm{veh.}}$	10.05	10.89	11.45	11.82	12.08	12.59

Table 1: *Costs for various time horizons. The present costs for user and agency, the marginal costs derived with respect to AADT, and the marginal costs calculated for one vehicle travelling for 100 km on a similar road. Note that all costs converge to a constant as the analysis horizon converges to infinity (right most column).*

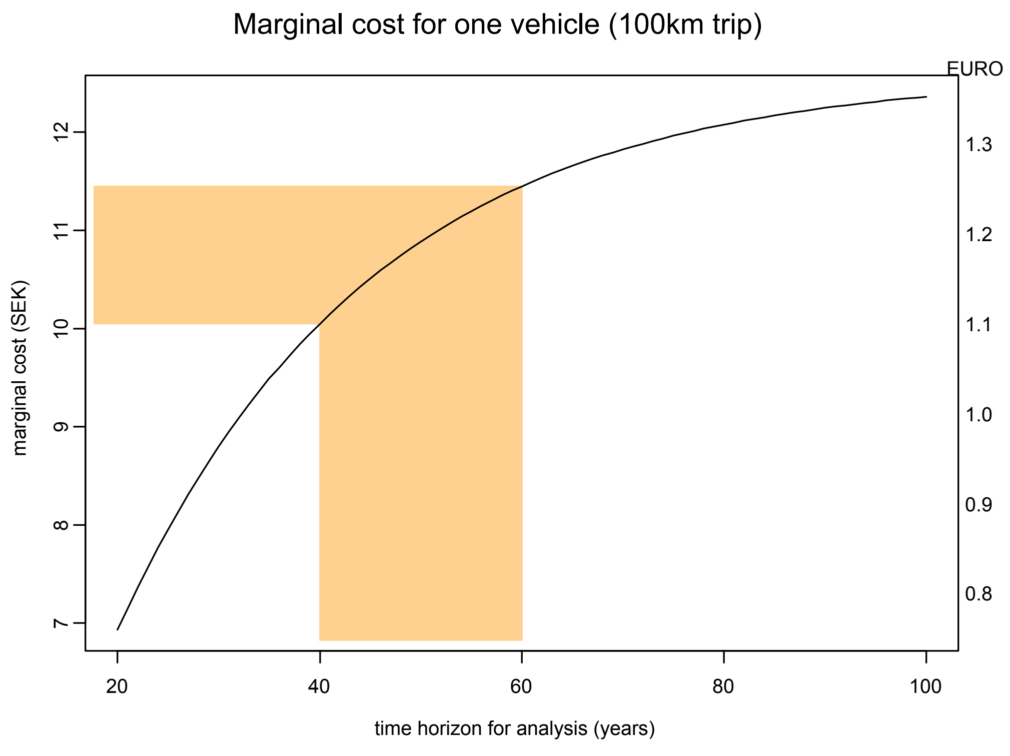

Figure 2: *As the time horizon for the analysis varies from 40 to 60 years, the marginal cost for a single vehicle under a 100 km long trip on a similar road varies from 10 to 11.5 SEK (1.1 to 1.25 EUR).*

5 Pitfalls in the analysis

This section focuses on the question if the technically feasible derivation of the marginal costs implicit in the Effektsamband 2000 documents is meaningful. We will argue that the interpretation of the results of such an operation are plagued with a problem regarding the identifyability of models in conjunction with the fact that Effektsamband 2000 was derived for a different purpose. Essentially, our concerns relate to that many useful models for planning maintenance activities should be build on strong associations between variables, but that derivatives with respect to traffic are only meaningful when the relevant relationships are of a causal nature. While it is widely recognized that association of variables does not imply causality, it is also true that causality does not imply association of variables. Thus, association and causality are different concepts.

This point is clarified by an example. Suppose that rutting is determined to be the critical factor for the user costs. Based on empirical observations for a particular type of road construction in a particular climate zone with roughly the same traffic loads, one has determined a quadratic relationship between the extend of rutting S and time t, $S(t)$, where time is the age of the pavement currently in service. Thus, one has empirically determined

$$S(t) = \alpha + \beta t + \delta t^2 \tag{4}$$

for some constants α, β, and δ. This is indeed the functional form suggested in SNRA (2001c, p. 35).

Suppose further that the cumulative number of equivalent single axle loads ($\mathrm{ESAL_{cum}}$) is roughly proportional to time, and that this property is shared by the accumulated average number of passing vehicles ($\mathrm{AADT_{cum}}$) in that well defined group of roads, implying that

$$\begin{aligned} \mathrm{ESAL_{cum}} &\approx c_{\mathrm{ESAL}} \times t\,, \quad \text{and} && (5)\\ \mathrm{AADT_{cum}} &\approx c_{\mathrm{AADT}} \times t\,, && (6)\end{aligned}$$

for some constants c_{ESAL} and c_{AADT}.

As a consequence, the model given in (4) could have been formulated as

$$S(\mathrm{ESAL_{cum}}) = \alpha + \frac{\beta}{c_{\mathrm{ESAL}}}\,\mathrm{ESAL_{cum}} + \frac{\delta}{c^2_{\mathrm{ESAL}}}\mathrm{ESAL^2_{cum}}\,, \tag{7}$$

or

$$S(\mathrm{AADT_{cum}}) = \alpha + \frac{\beta}{c_{\mathrm{AADT}}}\,\mathrm{AADT_{cum}} + \frac{\delta}{c^2_{\mathrm{AADT}}}\mathrm{AADT^2_{cum}}\,. \tag{8}$$

Now, taking the derivative of (4), (7) and (8) with respect of the relevant measure of traffic (loads) gives

$$\begin{aligned} \frac{d\,S(t)}{d\,\mathrm{traffic}} &= 0\,, && (9)\\ \frac{d\,S(t)}{d\,\mathrm{ESAL_{cum}}} &= \frac{\beta}{c_{\mathrm{ESAL}}} + \frac{2\,\delta}{c^2_{\mathrm{ESAL}}}\mathrm{ESAL_{cum}}\,, \text{ and} && (10)\\ \frac{d\,S(t)}{d\,\mathrm{AADT_{cum}}} &= \frac{\beta}{c_{\mathrm{AADT}}} + \frac{2\,\delta}{c^2_{\mathrm{AADT}}}\mathrm{AADT_{cum}}\,. && (11)\end{aligned}$$

Thus, the marginal change of rutting with respect to traffic is zero under model (4), but depends on the load if model (7) is used and is therefore different for heavy vehicles and passenger cars. If model (8) is applied, the marginal costs depend only on the number of vehicles and is of identical magnitude for heavy vehicles and passenger cars.

With respect to (statistical) model identification, models (4), (7), and (8) are equivalent under condition (5) and (6), because the variables contain the same information with respect to forecasting rutting. (If one would consider a multiple regression model with all three variables included, this would be revealed by problems of multicollinearity.)

With respect to the value of a model for a practitioner, it is certainly easier to calculate the time since last overlay than to get a perception of ESAL or AADT. Therefore, if the models would be intended to be used as forecasting rutting at particular times, model (4) would be preferable for that purpose. Furthermore, because time may capture even other features of importance like the approximate number of spring thaw periods the road was exposed to, model (4) may very well give better forecasts than (7) or (8) in situations of practical importance where the proportionality assumptions (5) and (6), respectively, might be relaxed.

The problem is that many useful models for planning maintenance activities are built upon associations between variables, but that derivatives with respect to traffic are only meaningful when the relevant relationships are of causal nature (at least in the relevant aspects). However, strong association of variables does not imply causality nor does causality imply association of variables. See Barnard (1982) for a short discussion of causation in scientific contexts or consult a general encyclopedia (such as the Encyclopedia Britannica) for the concept of causality in philosophy and science.

In essence, models successfully applied to forecasting road user conditions do not necessarily give valid derivations of marginal costs. The models utilized in the Effektsamband 2000 documents are generally designed to produce forecasts for different scenarios which are to be compared. They are not designed for deriving marginal costs and must not be used for this purpose without great care. In the particular case of evaluating maintenance strategies the models are clearly unsuitable for this purpose other than in very special circumstances. This should not be misinterpreted as a statement about the validity of the models for the purpose they were designed for.

6 Conclusions

It was argued that the typically delayed change to the worse for subsequent users of the road, initiated by a passing heavy vehicle, is a function of the damage caused by the strains and stresses from that heavy vehicle and the subsequent actions taken by the road agency. Therefore, marginal costs caused by the heavy vehicle cannot be assessed without investigating the maintenance strategies used by the road agency. Only the portion of marginal user and agency costs which are unavoidable under optimal maintenance strategies should be attributed to the additional vehicles.

However, *empirical* field-observations are only available for status quo maintenance strategies. Because empirically determined marginal costs combine the costs inevitably caused by the vehicles and the costs which might be avoidable if better maintenance strategies would be applied, empirically determined marginal costs can at their best provide an upper bound for the costs attributable to the heavy vehicles.

This was the reason for investigating the Effektsamband 2000 documents with respect to marginal costs inherent in the functional relationships applied in these documents. Because these documents are meant to give (among others) the means to conduct cost-benefit analysis for road projects and road maintenance, there must be assumptions about marginal costs present in the documents, at least implicitly, and we derived these implicit costs for a simple example of a periodically repeated maintenance action such as resurfacing.

To summarize our findings, models successfully applied to forecasting road user conditions do not necessarily give valid derivations of marginal costs. The models utilized in the Effektsamband 2000 documents are generally designed to produce forecasts for different scenarios which are to be compared. They are not designed for deriving marginal costs and must not be used for this purpose without great care. In the particular case of evaluating maintenance strategies the models are clearly unsuitable for this purpose other than in very special circumstances. Nevertheless, this should not be misinterpreted as a statement about the validity of the models for the purpose they were designed for.

Having that said, the relationships stated in the Effektsamband 2000 documentation are valuable for the determination of marginal costs in so far as they give a perception of how the SNRA intends to adapt its long run maintenance strategies to changes in traffic. It thus helps to provide estimates of marginal costs under status quo maintenance strategies, because it makes the decision process within the SNRA transparent.

References

Barnard, G. A. (1982). Causation. In S. Kotz and N. L. Johnson (Eds.), *Encyclopedia of Statistical Sciences: volume 1*, pp. 387–389. Wiley.

Bennett, C. R. (1996). The HDM-4 model. In *Proceedings of the 18th ARRB Transport Research Conference, Christchurch, New Zealand, 2–6 September*, Volume 4, pp. 67–82.

Brockenbrough, R. L. and K. J. Boedecker (Eds.) (1996). *Highway Engineering Handbook: Building and Rehabilitating the Infrastructure*. New York: McGraw-Hill.

Carnahan, J. V. (1988). Analytical framework for optimizing pavement maintenance. *Journal of Transportation Engineering 114*(3), 307–322.

Carnahan, J. V., W. J. Davis, M. Y. Shahin, P. L. Keane, and M. I. Wu (1987). Optimal maintenance decisions for pavement management. *Journal of Transportation Engineering 113*(5), 554–572.

Durango, P. L. and S. M. Madanat (2002). Optimal maintenance and repair policies in infrastructure management under uncertain facility deterioration rates: an adaptive control approach. *Transportation Research Part A 36*, 763–778.

Göransson, N.-G. and L.-G. Wågberg (2002). *Manual till den svenska nationella LTPP-databasen*. Linköping, Sweden: The Swedish National Road and Transport Research Institute. In Swedish.

Haas, R., W. R. Hudson, and J. Zaniewski (1994). *Modern Pavement Management*. Malabar, Florida: Krieger.

Huang, Y. H. (1993). *Pavement Analysis and Design*. Englewood Cliffs, New Jersey: Prentice-Hall.

Jara-Díaz, S. R., P. P. Donoso, and J. A. Araneda (1992). Estimation of marginal transport costs: The flow aggregation function approach. *Journal of Transport Economics and Policy XXVI*(1), 35–48.

Kerali, H. R., R. Robinson, and W. D. O. Paterson (1998). Role of the new HDM-4 in highway management. In *Proceedings Fourth International Conference on Managing Pavements, Durban, South Africa, May 17–21*, Volume 2, pp. 801–814. ISBN 0-620-22376-6.

Larsen, H. J. E., G. Hildebrand, and R. A. Macdonald (2002). Economic evaluation of pavement maintenance: PAV-ECO. Report 114, Danish Road Institute, Roskilde, Denmark.

Li, Y. and S. Madanat (2002). A steady-state solution for the optimal pavement resurfacing problem. *Transportation Research Part A 36*, 525–535.

Lindberg, G. (2002). Infrastructure cost case studies – case study 5b: Marginal cost of road maintenance for heavy goods vehicles on Swedish roads. UNITE (UNIfication of accounts and marginal costs for Transport Efficiency) deliverable 9, version 0.31, Swedish National Road and

Transport Research Institute (VTI), Project Co-ordinator: ITS, University of Leeds, Leeds. Funded by the European Commission, 5th framework – Transport RTD.

Link, H. (2002). Road econometrics – case study on renewal costs of German motorways. UNITE (UNIfication of accounts and marginal costs for Transport Efficiency) deliverable 10, version 1.1, German Institute for Economic Research (DIW), Project Co-ordinator: ITS, University of Leeds, Leeds. Funded by the European Commission, 5th framework – Transport RTD.

Madanat, S. M. and M. Ben-Akiva (1992). Optimizing infrastructure management decisions under measurement and forecasting uncertainty. In *Proceedings of 6th World Conference on Transport Research, Lyon, France*, Volume IV: Technological Innovation and Network Management, pp. 2413–2424. Laboratoire d'Economie des Transports. ISBN 2-908558-03-3.

Morse, A. A. and R. L. Green (1996). Pavement design and rehabilitation. See Brockenbrough and Boedecker (1996), Chapter 3.

OECD (1994). *Road Maintenance and Rehabilitation: Funding and Allocation Strategies*. Road Transport Research. Paris: OECD.

Ozbay, K., B. Bartin, and J. Berechman (2001). Estimation and evaluation of full marginal costs of highway transportation in New Jersey. *Journal of Transportation and Statistics 4*(1), 81–103.

Robinson, R., U. Danielson, and M. Snaith (1998). *Road Maintenance Management: Concepts and Systems*. London: Macmillan.

RRV (1986). Vägverkets underhåll av belagda vägar – en samhällsekonomisk granskning. Revisionsrapport Dnr 1986:248, Stockholm, Sweden. Review of the Swedish National Road Administration's maintenance routines by the Swedish Supreme Audit Institution (RRV), in Swedish.

Shahin, M. Y. (1994). *Pavement Management for Airports, Roads, and Parking Lots*. New York: Chapman & Hall.

Small, K. A., C. Winston, and C. A. Evans (1989). *Road Work – A New Highway Pricing and Investment Policy*. Washington, D.C.: The Brookings Institution.

SNRA (1989). *Effektkatalog – Drift- och underhållsåtgärder*. Borlänge, Sweden: Swedish National Road Administration, Publ 1989:18. In Swedish.

SNRA (2001a). *Effektsamband 2000*. Borlänge, Sweden: Swedish National Road Administration, Publ 2001:75–84. Collection of documents, in Swedish.

SNRA (2001b). *Effektsamband 2000: Drift och Underhåll – Effektkatalog*. Borlänge, Sweden: Swedish National Road Administration, Publ 2001:77. In Swedish.

SNRA (2001c). *Effektsamband 2000: Drift och Underhåll – Handledning*. Borlänge, Sweden: Swedish National Road Administration, Publ 2001:79. In Swedish.

SNRA (2001d). *Effektsamband 2000: Gemensamma förutsättningar*. Borlänge, Sweden: Swedish National Road Administration, Publ 2001:75. In Swedish.

SNRA (2001e). *Effektsamband 2000: Kollektivtrafik – Effektkatalog och handledning*. Borlänge, Sweden: Swedish National Road Administration, Publ 2001:82. In Swedish.

SNRA (2001f). *Effektsamband 2000: Nybyggnad och förbättring – Effektkatalog*. Borlänge, Sweden: Swedish National Road Administration, Publ 2001:78. In Swedish.

SNRA (2001g). *Effektsamband 2000: Nybyggnad och förbättring – Exempelsamling*. Borlänge, Sweden: Swedish National Road Administration, Publ 2001:81. In Swedish.

SNRA (2001h). *Effektsamband 2000: Nybyggnad och förbättring – Handledning*. Borlänge, Sweden: Swedish National Road Administration, Publ 2001:80. In Swedish.

SNRA (2001i). *Effektsamband 2000: Sammanfattning*. Borlänge, Sweden: Swedish National Road Administration, Publ 2001:84. In Swedish.

SNRA (2001j). *Effektsamband 2000: Sektorsuppgifter och myndighetsutövning – Effektkatalog*. Borlänge, Sweden: Swedish National Road Administration, Publ 2001:76. In Swedish.

SNRA (2001k). *Effektsamband 2000: Sökverktyg*. Borlänge, Sweden: Swedish National Road Administration, Publ 2001:83b. CD containing publications and a search program, in Swedish.

SNRA (2001l). *Effektsamband 2000: Sökverktyg – Handledning*. Borlänge, Sweden: Swedish National Road Administration, Publ 2001:83. In Swedish.

Tack, J. N. and Y. J. Chou (2001). Pavement performance analysis applying probabilistic deterioration methods. *Transportation Research Record 1769*, 20–27.

Thomas, F. (1997). Stochastic approaches to road maintenance and rehabilitation – state-of-the-art. CTS Working Paper 1997:03, Centre for Research on Transportation and Society, Dalarna University, Sweden.

Tighe, S. (2001). Guidelines for probabilistic pavement life cycle cost analysis. *Transportation Research Record 1769*, 28–38.

Tufty, H. G. (1996). Value engineering and life cycle cost. See Brockenbrough and Boedecker (1996), Chapter 10.

USDOT (1996). Exploring the application of benefit/cost methodologies to transportation infrastructure decision making. USDOT policy discussion series, no. 16, U.S. Department of Transportation, Federal Highway Administration.

Wågberg, L.-G. (2001). Utveckling av nedbrytningsmodeller: Sprickinitiering och sprickpropagering. VTI meddelande 916, The Swedish National Road and Transport Research Institute, Linköping, Sweden. In Swedish.

Wang, H. (2002). A survey of maintenance policies of deteriorating systems. *European Journal of Operational Research 139*, 469–489.

Watanatada, T., C. Harral, W. D. O. Paterson, A. M. Dhareshwar, A. Bhandari, and K. Tsunokawa (1987). *The Highway Design and Maintenance Standards Model – Volume 1. Description of the HDM-III Model*. The Highway Design and Maintenance Standards Series (The World Bank). Baltimore: John Hopkins University Press.

Wright, P. H. (1996). *Highway Engineering* (Sixth ed.). New York: Wiley.