Estimating the marginal costs for road infrastructure reinvestment[1]

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Draft

Jan-Eric Nilsson,
Swedish National Road and Transport Research Institute
Jan-eric.nilsson@vti.se
Kristin Svensson,
Dalarna University
kss@du.se
Mattias Haraldsson
Mattias.haraldsson@energimyndigheten.se

Abstract: This paper makes use of state-of-the-art modelling in order to assess the marginal cost for road infrastructure reinvestment based on a large set of data with information about sections of the road network, including their age. Although the modelling is straightforward, it is less so to estimate costs with acceptable quality, primarily since information about heavy vehicles is incomplete. The paper suggests a strategy for identifying major differences in marginal costs across the road network. In a longer perspective this provides a platform for establishing a disaggregate approach for charging heavy vehicles from their use of roads and

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[1] This paper is produced as an input for a government assignment to VTI to assess the social marginal costs for infrastructure use.

for channeling heavy traffic to the most modern and robust roads. The analysis also provides strong evidence for not only heavy vehicles but also cars contribute to road quality deterioration. The hypothesis is that this is due to the widespread use of studded tires in countries with regular freeze-thaw cycles.

1. Introduction

The estimation of (short-run) marginal infrastructure cost, i.e. costs related to additional vehicles using the infrastructure at large, has a long history. Today's understanding of this link between road use and costs is based on Newbery (1988) and in particular Small et al (1989).

There are at least four aspects of the estimation of marginal costs of road wear that have been dealt with by varying scholars. The first relates to the possibility that routine road maintenance, including snow clearance etc. may vary due to the extent of traffic using roads. This possibility is addressed by Haraldsson (2007) and has been updated by Swärdh & Jonsson (2014). Secondly, increasing the number of vehicles damages the infrastructure, leading to that future periodic maintenance is advanced in time, imposing an additional cost to society. This is the marginal cost related to traffic in focus here in the present paper.

Third, the relationship between vehicle weight and road wear is commonly believed to be non-linear, meaning that road quality primarily deteriorates with the weight on each vehicle axle. This necessitates a distinction to be made between the impact of heavy and light vehicles on road quality. The standard rule-of-thumb – the fourth power hypothesis – is also used in the present paper. And fourth, in countries like Sweden with pervasive freeze-thaw cycles, the use of studded tyres to enhance the vehicles' grip on icy roads may also have consequences for road wear and renewal. This aspect is addressed in the subsequent estimates.

To be precise, and using the dissertation of Haraldsson (2007) as a point of departure, the purpose of the present paper is to estimate the costs for road wear based on state-of-the-art modelling. This includes empirical assessment of whether it is only wear by heavy vehicles that drives deterioration. In addition, many previous studies have focused the estimation of *the* marginal cost for road wear as an all-encompassing average for the road network as a whole. This is taken a step further by seeking to identify possible differences in marginal costs across the road network. This will inter alia provide information of relevance for a discussion about the rationale for a non-uniform charging strategy.

Figure 1 illustrates the complex interrelationship between road design, usage and deterioration. Traffic in the centre box is decisive for both the design standard of a new road (arrow to the left) and for the deterioration of roads, once they start to be used (rightward arrow). The more traffic that is expected on a road, the more robust is the design standard (thickness of sub- and superstructure). At the same time, the more traffic using an existing road, the faster is the deterioration. However, if the road was initially built to tolerate much traffic, deterioration may still be slow. This interrelationship colours much of the subsequent analysis.

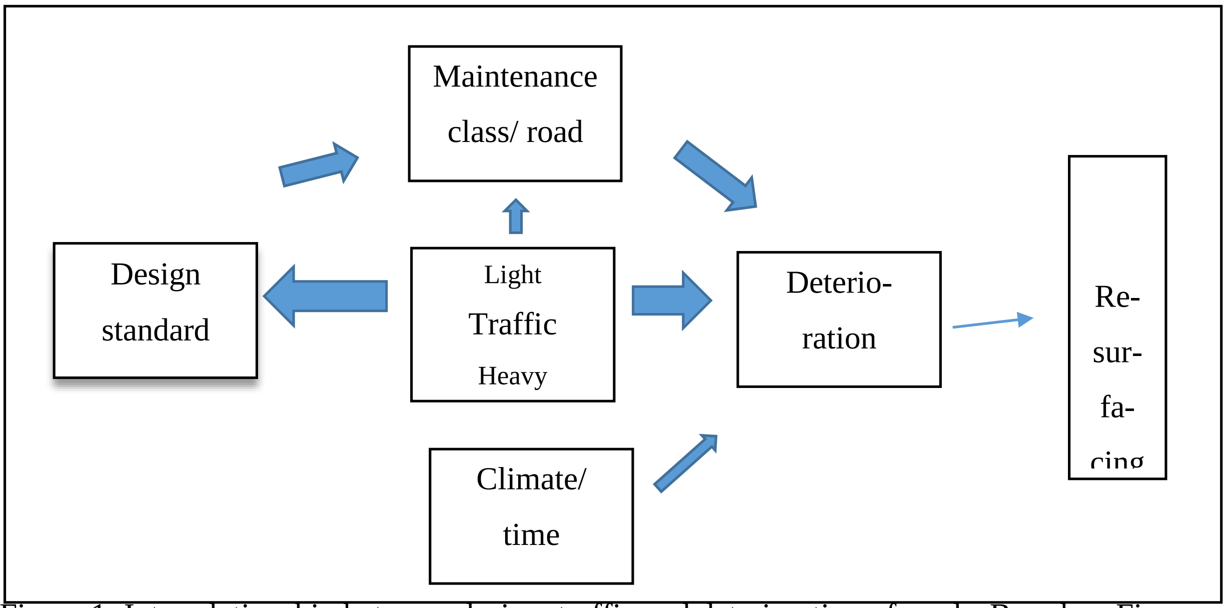

Figure 1: Interrelationship between design, traffic and deterioration of roads. Based on Figure 2.1 in Haraldsson (2007).

On top of this two-sided association comes another two features. The combination of traffic and design standard provides the basis for the strategy for on-going maintenance of a road (the top-most rectangle). In the same way as in most European countries, Sweden has a classification that distinguishes between international, national and regional roads. Although the road class correlates with the extent of traffic, there may well be sections of an international road that have less traffic while parts of local roads may be heavily used. Irrespective of the detailed structure of the policy, road category affects maintenance that in turn may have consequences for the degree of deterioration.

A further feature of the interrelationship is climate or time per se (the bottom-most rectangle), as road surface standard may deteriorate independent from use. This is a subject where engineers do not seem to agree, the common belief in Sweden being that there is no quality deterioration separate from usage.

The paper starts in section 2 by using the basic components of the model suggested by Small et al (1989) for the analysis and for identifying the type of data necessary for making the relevant calculations. We also describe where the previous analysis is extended. Section 3 analyses costs for re-surfacing in order to generate an average-cost measure that provides the basis for he analysis. Section 4 applies a time-to-event model for estimating the traffic that has used roads between “birth” and “death” of a pavement. Section 5 summarises results, including a comparison of previous approaches to make the same type of calculations. Haraldsson (2007) reviews the literature and no additional state-of-the-art summary is therefore included in the present paper.

2. The modelling framework

The calculation of marginal reinvestment costs comprises two main components. Firstly, it is necessary to establish an economic model for the present value calculations; this is done in section 2.1. An essential input of this model concerns the life-length of roads. Engineering aspects described in section 2.2 provides a crucial input for these calculations. While these sections treat all vehicles as being identical, section 2.3 elaborates on the implications for cost estimation of vehicle/axle weight. Section 2.4 summarises the framework section by formulating testable hypotheses.

2.1 The economic model

Figure 2 captures the framework for the economic analysis. The solid line characterizes the reduction of quality of a piece of infrastructure as time goes and as more and more vehicles have used the road. At some point of time, t^*, quality reaches a critical standard (π_f), and as a result the standard has to be restored, ideally to the original level (π_0). After that, the degradation starts once again.[2] The mirror image of this graph describes increasing costs for road maintenance as well as for users up to the date of renewal.

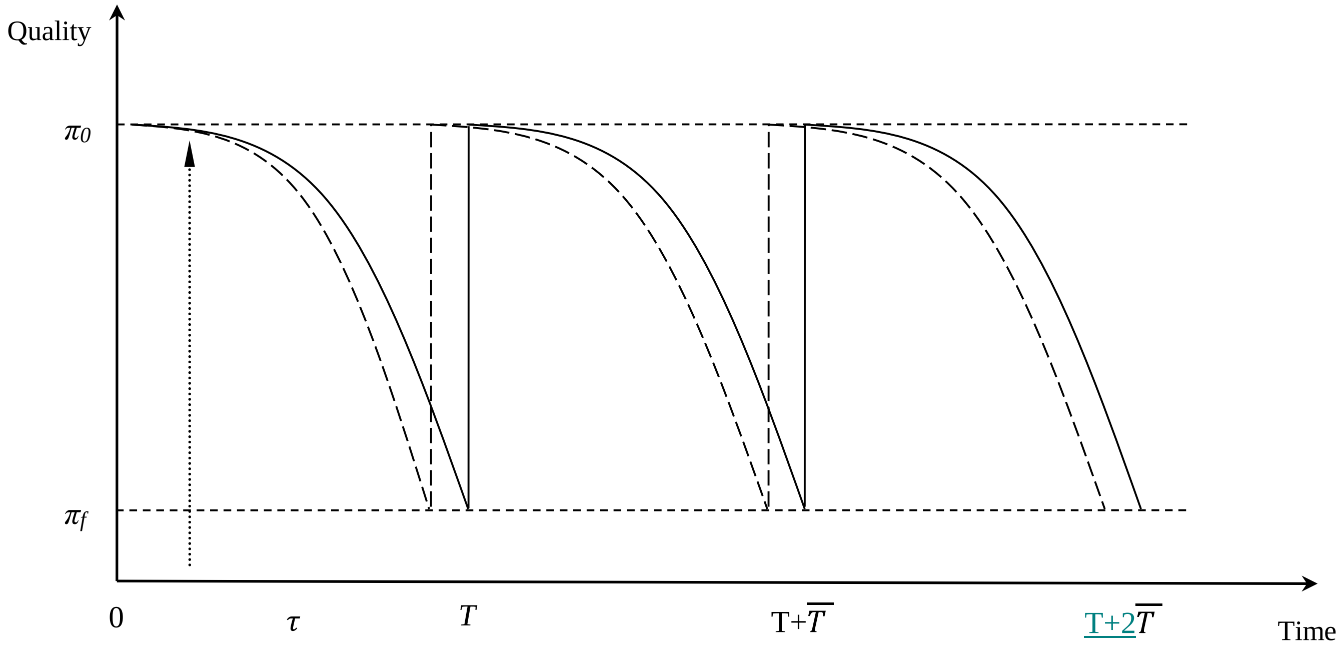

Figure 2. Renewal intervals with and without a marginal increase in traffic at time $\tilde{t}$.

The pattern of deterioration-rehabilitation cycles is based on expectations regarding future traffic when the road is originally built. The analytical trick of the model is to assume that, at some point of time, $\tilde{t}$, traffic increases relative to the ex ante belief. The consequence of the unexpected (one-time) addition of traffic, and therefore also wear, is that the critical quality level will be reached slightly earlier than predicted, making it necessary to frontload the rehabilitation activity. Spending on rehabilitation earlier than planned represents a cost to society. Since the frontloading effect continues for the foreseeable future, the rather small cost increase the first period may increase the present value of resurfacing substantially. The extent of the cost increase is related to the frequency of resurfacing activities and the level of the discount rate.

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[2] Quality is here handled as if it was a well-defined concept, which it is not. It is however not necessary to dwell on the challenges involved in measuring quality. The assumption is simply that engineers have established some critical level of standard that triggers resurfacing. This limit value also defines the life of the pavement.

In order to model these costs, let C represent the cost per square metre for a resurfacing activity. After time T a new road surface is laid every $\overline{T}$ years, the bar representing the constant time interval. Equation (1), where r denotes the discount rate, defines the present value of all future overlay costs (PVC).

$$PVC_T = \frac{C}{(1-e^{-r\overline{T}})} \qquad (1)$$

The consequences of an unexpected increase in traffic at any time $\tau<T$, the present value of costs has to be discounted from the precise time of the shock.[3] The present value of all future pavement renewal costs after τ is given by eq. (1') where $v = T - \tau$ is the remaining life of the pavement;

$$PVC_\tau = \frac{C}{(1-e^{-r\overline{T}})} e^{-rv} \qquad (1')$$

Differentiating (1') with respect to annual traffic (Q) provides the marginal costs (MC);

$$MC = \frac{\partial PVC}{\partial Q} = \frac{\partial PVC}{\partial T}\frac{dT}{dQ} = -Cr\frac{e^{-rv}}{(1-e^{r\overline{T}})}\frac{\partial v}{\partial T}\frac{dT}{dQ} \qquad (2)$$

Following Lindberg (2004), it is instructive to rewrite this expression in terms of changes in annual average traffic $\overline{Q}$; in the absence of traffic growth, $Q = \overline{Q}$. He also defines deterioration elasticity (ε) as $\varepsilon = {}^{\delta T}\!/_{\delta\overline{Q}} * {}^{\overline{Q}}\!/_{T}$. This is a measure of the responsiveness in pavement life to a change in average traffic intensity. The relation between a momentary traffic change and deterioration elasticity is approximatively given by eq. (3); the approximation is related to that a small shift in traffic intensity at time τ leads to a shift in the average traffic volume over the whole period equal to $1/T$:

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[3] Small et al (1989) work with an annualized value of the Present Value Cost, i.e. $r*PVC$. In addition, they handle the external change as if it happened in the same instance as when the renewal was still to take place and therefore uses (1) rather than (1').

$$\frac{\delta T}{\delta Q_\tau} = \frac{\delta T}{\delta \overline{Q}_I}\frac{\delta \overline{Q}_I}{\delta Q_\tau} = [\frac{\delta \overline{Q}_I}{\delta Q_\tau} \approx \frac{1}{T}] = \frac{\varepsilon}{\overline{Q}_I} \tag{3}$$

Using this, and since ${}^{\partial v}/_{\partial T} = 1$, eq. (2) can be rewritten as eq. (2').

$$MC_\tau = \frac{\partial PVC}{\partial Q} = \frac{\partial PVC}{\partial T}\frac{dT}{dQ} = -Cr\frac{e^{-rv}}{(1-e^{r\overline{T}})}\frac{\varepsilon}{\overline{Q}_I} \tag{2'}$$

The average MC over all possible remaining lifetimes from the date of the traffic increase is the expected marginal cost taken over a probability density function of v, $g(v)$:

$$E[\frac{\partial PVC}{\partial Q}] = -\frac{Cr\varepsilon}{\overline{Q}_I}\int_0^\infty \frac{e^{-rv}}{\left(1-e^{r\overline{T}}\right)} g(v)dv \tag{3}$$

If the pavement deteriorates deterministically with traffic and the lifetime of a pavement comes to its end exactly when its quality falls to a predetermined level, $g(v)$ is uniform, i.e. $g(v) = {}^{1}/_{T}$. Under this assumption, eq. (3) can be written in the following way:

$$E\left[\frac{\partial PVC}{\partial Q}\right] = -\frac{Cr\varepsilon}{\overline{Q}_I}\frac{1}{\left(1-e^{r\overline{T}}\right)}\left[-\frac{1}{r}e^{-rv}\right]_0^T = -\varepsilon\frac{C}{\overline{Q}_I T}\frac{(1-e^{rT})}{\left(1-e^{r\overline{T}}\right)}$$

If, moreover, all future pavement renewals have the same time interval as the present $\overline{T} = T$, this further collapses to the below expression. The expected marginal cost is then equal to the deterioration elasticity times the average reinvestment cost (the quotient in the below equation):

$$E\left[\frac{\partial PVC}{\partial Q}\right] = -\varepsilon\frac{C}{\overline{Q}_I T}$$

We assume, however, that pavement lifetime T is not deterministic but model the life of pavements by using a Weibull function; the motive is given in the next section. The survival function of a Weibull function implies the following pdf. for remaining lifetimes:

$$g(v) = \frac{e^{-\gamma v^\alpha}}{E[T]}, 0 < v < \infty$$

Substituting this into eq. (3) gives eq. (4). The first two components of this expression are the same as in the deterministic version. The third component is related to the discounting and uncertainty with respect to when in the period between an almost new pavement (t=0) and a pavement that is about to be replaces that the external shock takes place (t=τ).The fourth component allows for uncertainty with respect to when the pavement's life ends.

$$E[\frac{\partial PVC}{\partial Q}] = -\varepsilon \frac{C}{E[T]\overline{Q}_I} \frac{r}{\left(1-e^{-r\bar{\bar{T}}}\right)} \int_0^{\infty} e^{-r\upsilon-\gamma\upsilon^{\alpha}} d\upsilon \qquad (4)$$

2.3 The engineering model

The input for calculating expected marginal costs as depicted by eq. (4) requires information about costs (C) and the life of a pavement ($\overline{T}$). Postponing the derivation of costs to section 3, the present section elaborates on the engineering aspects of the problem in order to derive an estimate of average pavement life.

A road and its pavement is designed to withstand a certain number of vehicle passages before requiring treatment such as a new surface layer. As explained above, the road is resurfaced once pavement quality (π) reaches the value $\pi_f < \pi_0$. Following Small et al (1987), the quality of a (section of) road can be assumed to deteriorate over time in the way depicted by eq. (5) where $\overline{N} = \sum_{t=0}^{T} Q_t$, i.e. the aggregate number of vehicles over the road's life cycle. The latter number is obviously a derivative of the quality that triggers the reinvestment, π_f.

$$\pi(t) = \pi_0 - (\pi_0 - \pi_f)(\frac{Q*t}{\overline{N}})e^{mt} \qquad (5)$$

Except for the degree of use, the exponential part of eq. (5) indicates that pavement roughness may increase at a rate $0 \leq m \leq 1$ that is independent of wear. With m=0, road quality is proportional to cumulative traffic ($Q*t$). The presence of the m-variable may represent several features. Figure 1 points to that ageing per se may affect the standard, meaning that even a road that is not used would decay. Deterioration could possibly also be affected by weather or climate, meaning that different countries may see their roads deteriorate in different ways.

One way to empirically model the quality deterioration is to use a Cox proportional hazards model. This is a semi-parametric approach, meaning that no assumption of a specific distribution of the data about ageing is required. The hazard is said to be proportional since the ratio between the hazards of two road sections with different values of one covariate is constant. Using that modelling approach, the expected life of a certain pavement or road section is not affected by when it was originally built.

Svensson (2014) uses a Cox model but, following Haraldsson (2007), we rather assume that T follows a Weibull distribution with parameters $\gamma>0$ and $\alpha>0$. The Weibull distribution function ($F(t)$), survival function ($S(t)$) and hazard function ($\lambda(t)$) are represented below; the probability density function of remaining lifetimes υ was established in section 2.2.

$$F(t) = 1 - e^{-\gamma t^{\alpha}}$$
$$S(t) = e^{-\gamma t^{\alpha}}$$
$$\lambda(t) = \gamma \alpha t^{\alpha-1}$$

Of particular interest is the hazard function. In the present application, the hazard rate indicates the chance that a pavement will be replaced at time t, given that it has lasted so long. Following Kiefer (1988), explanatory variables can be introduced in the Weibull model using a proportional hazard:

$$\lambda(t) = f(X) t^{\alpha-1}$$

Replacing the exponential weather variable m in eq. (5) by a power function, $t^{\delta-2}$, we get an expression describing the deterioration of road quality over time akin to the proportional Weibull hazard:

$$\pi_t = \pi_0 - (\pi_0 - \pi_f)\frac{Qt}{N} t^{\delta-2} = \pi_0 - (\pi_0 - \pi_f)\frac{Q}{N} t^{\delta-1} \tag{5'}$$

With this formulation, $\delta>2$ implies the presence of a weather effect while road quality is proportional to $Q*t$ (cumulative traffic) if $\delta\leq2$. It is straightforward to interpret equation (5’) as an increasing hazard indicating that the road lifetime will more probably end if it has lasted a long time. Normalizing the road quality so that initial quality is zero, $\pi_0 = 0$, we get the proportional Weibull hazard:

$$\lambda(t) = \pi_f \frac{Q}{N} t^{\alpha-1}$$

Kiefer (1988) demonstrates that this hazard is equivalent to a log linear lifetime function. In equation (6) ϵ is a random error term following an extreme value distribution and parameters for Q and N are introduced in order to make the model more general. In terms of the economic model in eq. (4), $-\beta_Q/(\alpha-1)$ is the deterioration elasticity.

$$-\propto lnT = ln\pi_f + \beta_Q lnQ - \beta_N lnN + \epsilon \tag{6}$$

2.3 Light and heavy vehicles

Before deriving the information necessary for estimating eq. (4) it is necessary to elaborate on the treatment of traffic. Eq. (5’’) in combination with eq. (7) facilitates an analytical separation of heavy and light vehicles in the deterioration process. Starting with eq. (7), y is the number of days per year; using a traffic-per-day statistic is the standard way in the industry to represent traffic information. q_i is the average number of vehicles of class i per day and there are $i=1,\ldots,I$ classes of vehicles. One of these, class j, represents passenger vehicles while all other classes refers to different weight and axle configurations of heavy vehicles.

$$\lambda(t) = \pi_f \frac{\sum \mu_i q_i}{N} t^{\alpha-1} \tag{5''}$$

$$\mu_i = y * \sum_{a=1}^{P} k_{ia} \cdot \left(\frac{W_{ia}}{10} \right)^4 \tag{7}$$

μ_i in eq. (5’’) is used for transforming the number of (heavy) vehicles in each vehicle class into “standard axles” using the universally agreed Equivalent Standard Axle Load (ESAL) concept. One ESAL is a single axle of 18 000 pounds, (8 164 kg). Vehicles in all I classes are therefore converted to being ESAL vehicles. In this, $a=1\ldots P$ denotes the axles (or axle groups) for vehicle type i with P=8 typically being the maximum number of vehicle axles (groups). W_a is the weight (tons) on axle (group) a which is divided by 10 for normalisation purposes. Weight is then raised to the fourth power, meaning that an increase from 8 to 10 tonnes per vehicle axle does not increase wear of vehicle type μ_i by (10/8=) 25 but by $((10/8)^4=)$ 144 percent.

In Table 1 the number of standard axles has been computed for various vehicle classes and numbers of axles using the fourth power rule. The first row represents a 7.5-ton standard Rigid Truck that has two, possibly three axles. Irrespective of which, this vehicle’s impact is $0.002 \leq \text{ESAL} \leq 0.008$, i.e. its road wear is minimal.

Table 1: Number of standard axles (ESAL) for various combinations of vehicles classes and number of axles. RT - Rigid Truck; AT - articulated truck; the number refers to total vehicle weight in ton. Grey squares indicate where μ_i changes from being below to above 1. Lindberg (2006).

Vehicle type *i*	**Number of axles**									
	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
RT7.5	0.008	0.002	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000
RT12	0.113	0.033	0.014	0.007	0.004	0.003	0.002	0.001	0.001	0.001
RT14	0.357	0.106	0.045	0.023	0.013	0.008	0.006	0.004	0.003	0.002
RT20	1.044	0.309	0.131	0.067	0.039	0.024	0.016	0.011	0.008	0.006
RT26	3.498	1.036	0.437	0.224	0.130	0.082	0.055	0.038	0.028	0.021
RT28	6.643	1.968	0.830	0.425	0.246	0.155	0.104	0.073	0.053	0.040
RT32	10.125	3.000	1.266	0.648	0.375	0.236	0.158	0.111	0.081	0.061
RT32+	15.743	4.665	1.968	1.008	0.583	0.367	0.246	0.173	0.126	0.095
AT28	4.883	1.447	0.610	0.313	0.181	0.114	0.076	0.054	0.039	0.029
AT34	11.544	3.420	1.443	0.739	0.428	0.269	0.180	0.127	0.092	0.069
AT40	23.427	6.941	2.928	1.499	0.868	0.546	0.366	0.257	0.187	0.141
AT50	51.258	15.188	6.407	3.281	1.898	1.196	0.801	0.563	0.410	0.308
AT50+	114.383	33.891	14.298	7.321	4.236	2.668	1.787	1.255	0.915	0.688

A 26-ton Rigid Truck has an ESAL just above one if it is equipped with three axles while the ESAL is 0.473 if it has four axles. For each specific vehicle type, the number of standard axles decrease when the number of axles increases, since the weight per axle then decreases. Thus, a larger number of axles will cause less road deterioration for each vehicle class.

The rule per se emanates from empirical test is the US mid-west made in the late 1950ties. Moreover, re-estimating the original data using more up-to-date econometrics, Small et al (1987) confirms the result, landing a coefficient of 3.7.

While the fourth power rule of thumb has been challenged, no alternative has been suggested. As part of our government assignment, resources have been made available for using the institute's Heavy Vehicle Simulator (HVS) to test this rule-of-thumb. This is done by building roads with different strength and then wear down each road in a "lab" in order to establish when it reaches the critical quality level.[4] Three road types are tested, with type 1 being modern and well built while types 2 and 3 are of older standard. Each road type is tested with three different weights - 8, 10 and 12 ton per axle pair. The equipment makes about 22 000 passages per full day corresponding to 150 000 passages per week. Somewhere between 300 000 to 600 000 passages are required in order to break down the surface – to create ruts – that are large enough to warrant resurfacing.

Figure 4 provides an image of the results testing the best, type 1 road. The most striking observation is that the measurement results are very close to the fourth power rule-of-thumb. To be sure, the trials are not able to generate statistically robust results. It does, however, point to a way for taking this type of analysis one step further. Moreover, it does not contradict the use of the fourth power hypothesis in the present paper.

Except for addressing the distinction between vehicles with different weight, the rule has a clear implication for the impact of light vehicles on resurfacing decisions. A 1,6 ton car with the same weight on both axles corresponds to $6{,}3 \cdot 10^{-6}$ ESAL. The wear of passenger vehicles in this dimension is therefore very small.

There is, however, a separate discussion about passenger vehicles damaging pavements due to the use of studded tyres. In countries like Sweden with repeated freeze-thaw cycles each winter, studded tyres are even compulsory for passenger vehicles. Since we have access to detailed information, it will be feasible to address the possibility that not only heavy but also passenger vehicles are of relevance for road quality deterioration. This is done by way of

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[4] Further information is available at http://www.vti.se/en/vti-offers/accelerated-testing-road-construction/

representing usage in terms of heavy vehicles/ESAL as well as the number of passenger vehicles in the estimation of pavement life. In equation (6), Q is then separated into Q_{-j} and Q_j, the first accounting for average ESAL of all heavy vehicles and the latter the number of passenger vehicles using each road section.

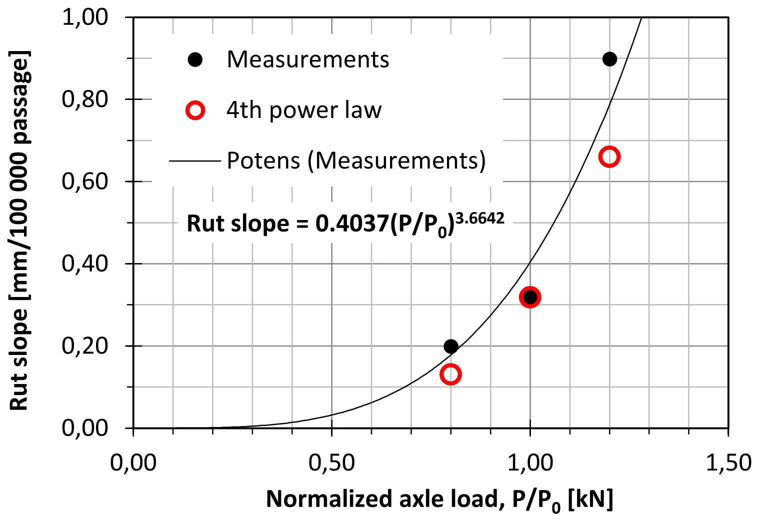

Figure 3: Rutting increase (mm/100,000 passages) as a function of normalized axle load for road type 1. From Erlingsson (2014).

2.4 Summary

To summarise, eq. (4) establishes the way in which expected marginal costs relating to the impact of traffic on the need for reinvestment is to be calculated. Section 2.2 has elaborated on the way in which road quality deteriorates over time while section 2.3 has emphasised the need to distinguish between heavy and light vehicles. While the difference between vehicle types has a huge impact on the numerical outcome of the estimations, it does not affect eq. (4). The only consequence is rather that Q (and N) is not conceived of as vehicles at large but ESAL's of heavy vehicles and the number of passenger vehicles.

The generation of information for estimating marginal costs as defined by equation (4) therefore means that three hypotheses are tested against available data: Quality deteriorates due to the extent of heavy vehicles, measured as ESALs (hypothesis 1), the number of light vehicles (hypothesis 2) and time, independently from the extent of traffic (hypothesis 3).

3. Calculating reinvestment costs

The Swedish Transport Administration's, subsequently *Trafikverket,* tenders all maintenance and reinvestment activities. 285 resurfacing contracts, tendered during 2012 and 2013, have been made available for deriving a value of average cost for resurfacing, i.e. C. Contracts range in size from just over SEK 1 million to SEK 65 million; the smallest contracts are below 1000 m^2, the largest being 2.2 million m^2.

This information has been employed to calculate the average cost for the country as a whole as well as for each region and pavement method. The three methods are referred to as warm, half-warm and tank lining. The average cost derives from observed cost for each contract and the respective contract size measured by square meters (m^2). The national average is calculated using the relative size ($\sum_i m_i^2$) as weight for region and type of pavement. In two regions, no tank-lining and half-warm contracts have been tendered during these two years. Since there indeed are roads with these qualities of pavement also in these regions, the average for the respective category has been imputed in these cells.

Table 5 demonstrates that average cost for a contract is SEK 87 per m^2. Contracts for tank-lining are much cheaper per m^2 than the other types of surfacing. This is as expected since this approach primarily is used on roads with less than 1000 vehicles per average day. It is less obvious why black tops laid using materials defined to be "warm" are less expensive per m^2 that half-warm pavements in view of the apparent simplicity of the latter. One explanation is that the half-warm pavement is used on roads with intermediate traffic levels (between 1000 and 7000 vehicles per average day) that may not have been built to standard from the beginning. If this is correct, and if a substantial number of heavy vehicles uses this class of roads, the resurfacing activity in reality represents a rehabilitation project. To the extent that the cost is triggered by inappropriate surface standard, and since contracts may have this quality, the choice has been made to use this figure in the estimations of marginal costs.

4. Estimating pavement life

Trafikverket's Pavement Management System (PMS) is used for storing data collected during annual road quality measurement activities. The system also registers information about when a road is "treated" in different ways, including when major pavement renewals are carried out.

In addition, it includes information about traffic using each road segment. Section 4.1 provides further information about this dataset, section 4.2 details the Weibull model used for estimating pavement life while section 4.3 presents the results.

Table 5: Average cost per contract in six regions and for three types of pavement. 2012 and 2013, SEK/m^2. None – no contract using this method has been tendered in this region. Number within brackets has been imputed using the average cost for this method.

		Method			
Region		Tank-lining	Half-warm	Warm	Total
M.	Average cost, SEK	26	127	110	98
	No. of contracts	8	9	19	37
	$\sum_i m_i^2$ million	5.1	1.9	4.2	11.3
N.	Average cost, SEK	21	148	108	124
	No. of contracts	4	25	19	50
	$\sum_i m_i^2$ million	4.1	2.8	2.9	9.9
St.	Average cost, SEK	31	(124)	100	97
	No. of contracts	1	No tender	29	30
	$\sum_i m_i^2$ million	0.5	-	2.6	3.1
S.	Average cost, SEK	38	(124)	78	68
	No. of contracts	13	No tender	42	55
	$\sum_i m_i^2$ million	2.6	-	4.8	7.4
V.	Average cost, SEK	21	79	81	71
	No. of contracts	10	9	45	64
	$\sum_i m_i^2$ million	3.4	3	5.7	12.1
E.	Average cost, SEK	20	101	86	78
	No. of contracts	11	13	25	49
	$\sum_i m_i^2$ million	5.1	2.1	6	13.2
Total	Average cost, SEK	27	124	90	87
	No. of contracts	47	56	179	285
	$\sum_i m_i^2$ million	20.7	9.7	26.1	56.8

4.1 Data

The 2012 version of the PMS comprises 390,966 observations of homogeneous road sections. Sections vary in length, from over one kilometer to only a few meter. Only sections that are 50 meters or longer have been retained for the analysis. The elimination of short sections in combination with other quality controls has made 266,614 road sections relevant to use in the analysis.

A lot of information is available about each homogenous road section. This includes which out of five different width classes that the section belongs to as well as the precise type of pavement laid, facilitating the estimation of life expectancy on a very disaggregate level. The previous section however demonstrated that information is less opulent about resurfacing costs. As a consequence, the only type of information that can be used for estimating marginal costs at a disaggregate level is three main categories of pavement spelled out by table 2. Since each of the six regions tender these contracts, 18 different cost observations are available. Except for possible managerial differences, the dummy for regions may capture differences with respect to climate, the situation in the north of the country being different from those in the south.

Table 3 summarizes some descriptive information of the data. The fifth column illustrates the strong dominance of traffic on roads with the most expensive type of pavement. Svensson (2014) provides an analysis including many more covariates and also describes the way in which data has been compiled.

The final step in the handling of input data concerns the way in which heavy traffic is converted to ESAL. The information on this count is extremely poor. Since at least 2004, *Trafikverket* however collects information about vehicle weight at 12 places across the country using a Bridge Weigh-in-Motion (BWIM) system inter alia registering the number of axles and axle configuration as well as total vehicle weight. This provides a type of information appropriate for the present purpose, except that 11 of the 12 measuring points are located on major roads, here represented by the “warm” pavement technology. Only one measurement point is on a place with the cold-type of pavement, and this spot is located close to a saw-mill, generating a non-average result; see further Erlingsson (201x).

For the present analysis the following values are used for converting the number of heavy vehicles to ESAL: major roads with hot pavement, 1.1; cold pavement type 0.9; surface dressing 0.6 if the share of heavy traffic is below 13 percent; 1.5 if it is 13 percent or higher.

Table 3: Descriptive statistics of traffic and road length within each region and surface category registered year 2012. Source: *Trafikverket* PMS system.

Region	Surface category	Traffic (million vehicles/ year)	Road length (km)	Average no. of vehicles/road km, million	Thereof heavy traffic (%)
M	Cold	3511	88696	19,3	9
M	Surface dressing	7505	9458	42,3	11
M	Hot	16741	6513	105,3	9
N	Cold	4351	10529	27,4	12
N	Surface dressing	2680	5446	16,7	13
N	Hot	7327	2639	54,4	10
Sthlm	Cold	87	232	0,4	8
Sthlm	Surface dressing	3512	4112	20,3	8
Sthlm	Hot	66434	4509	506,9	7
S	Cold	1480	4939	7,6	8
S	Surface dressing	6493	14374	34,6	10
S	Hot	47297	14495	293,1	11
V	Cold	1803	5558	9,8	6
V	Surface dressing	9668	12095	55,5	10
V	Hot	53470	9362	358,6	10
E	Cold	968	2839	5,3	7
E	Surface dressing	9613	13671	54,5	9
E	Hot	37874	8999	234,7	10

4.2 Modelling life length

In order to compute the expected marginal present value cost it is necessary to estimate the deterioration elasticity, ε, and the Weibull parameters α and γ. As before, $\bar{Q}$ is the traffic volume during an average year between the year the original pavement was spread and its final year, $\bar{T}$. Heavy traffic is represented as Q_{ESAL} and the number of passenger vehicles Q_{car}. Instead of N (the amount of traffic a road can bear before renewal) and π(f), the critical level of road quality, that are both unobserved, we use a vector of covariates $\boldsymbol{M}$ that may have an impact on the pavement lifetime, including a constant, in order to provide a consistent estimate of the traffic coefficient. A linear model is then given by eq. (7). representing the empirical equivalent of eq. (4):

$$-\alpha lnT = lnQ_{car}\beta_{Q_{car}} + lnQ_{ESAL}\beta_{Q_{ESAL}} + \beta_{\boldsymbol{N}}\boldsymbol{M} \quad + u \tag{7}$$

Estimated coefficients $\beta_{Q_{car}}$ and $\beta_{Q_{ESAL}}$ are used for testing hypothesis 1 and 2 respectively. If these coefficients are significantly different from zero they will signal the impact of heavy traffic and passenger vehicles on reinvestment costs. If so, the coefficient values will also be used for calculating marginal costs of the respective coefficients.

In addition, the value of $\hat{\alpha}$ is used for testing the hypothesis that there is an independent time/weathering effect on the hazard of a road being “treated”. Specifically, if $\hat{\alpha} > 2$ the last component of eq. (5’) makes the hazard increase at an increasing rate with time. This is then our test variable.

Having estimates of $\hat{\beta}_{\overline{Q}_j}$, $\hat{\beta}_{\overline{Q}_{-j}}$ and α will also make it feasible to compute the deterioration elasticity.

$$\hat{\varepsilon}_{ESAL} = \frac{\delta lnT}{\delta lnQ_{ESAL}} = -\frac{\hat{\beta}_{Q_{ESAL}}}{\hat{\alpha}} \text{ and } \hat{\varepsilon}_{car} = \frac{\delta lnT}{\delta lnQ_{car}} = -\frac{\hat{\beta}_{Q_{car}}}{\hat{\alpha}}$$

3.3 Results

Table 3 provides the results of the estimates of eq. (7). As expected, the large number of observations provides for very precise estimates. Cold surfaces and surface dressing have statistically significantly shorter life than warm pavements. Moreover, Stockholm’s roads last shorter time than roads in the other regions; region M roads “live” about 13 percent longer time than region Stockholm roads. The reason is probably that even though roads in Stockholm are robustly built at large, traffic is much higher than in the other regions.

Table 3: Estimates of surface life length using a Weibull model. 252 309 observations of homogeneous road sections. * - reference category.

	Coefficient	Std. Error	Z	p-value
Intercept	4,0268	0,01427	282,1	0,0000
$\hat{\varepsilon}_{ESAL}$	-0,0888	0,00195	-45,44	0,0000
$\hat{\varepsilon}_{car}$	-0,1033	0,00256	-40,42	0,0000
Hot*	0			
Cold	-0,2404	0,00501	-48,03	0,0000
Surface dressing	-0,1431	0,00395	-36,27	0,0000
Sthlm*	0			
M	0,1382	0,00697	19,82	0,0000
N	0,2371	0,00765	30,97	0,0000
S	0,1921	0,00663	28,97	0,0000
V	0,2024	0,00675	29,98	0,0000
E	0,0247	0,00667	3,71	0,0002
Log(1/alpha)	-0,4765	0,00191	-249,83	0,0000
Alpha	1,61			

Based on table 3, hypothesis 3 is rejected while hypotheses 1 and 2 are not: Both light and heavy vehicles affect the timing of resurfacing activities and consequently the life length of pavements, while there are no other, external aspects such as weather that does. Bearing in mind that information about how heavy vehicles are "translated" into ESAL, it is noteworthy that the impact of passenger vehicles on surface life is stronger than the consequences of variations in heavy vehicles.

The maintained hypothesis is that the significance of the coefficient for cars goes back to their use of studded tires. If this hypothesis is correct it is reasonable if cars' road wear in the north of the country is at a lower level than in the reference, Stockholm region in the middle of the country. This is so since the road surface furthest north is covered by snow and ice for longer periods than in the southern parts of the country, meaning that the studs do not wear down the pavement for so long periods. In addition, roads in the southern parts of Sweden have less harsh winters than up north, meaning that fewer cars use studded tires.[5] Interacting cars and regions provides an indication of that this may be correct. Compared to Stockholm, the car-region coefficient is some 20 percent higher for regions North, South and West while roads in regions East and Middle last about 10 percent longer.

The results in table 3 are used in order to estimate life length based on car traffic and ESAL as summarized in table 4. Median lifetime is strikingly similar across surface types and regions.[6] Hot pavements live slightly shorter times in spite of being more robust. Most probably, the reason is that they are used by much more traffic at large than roads with other types of surface treatment.

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[5] SMHI (2008) indicates that 44 percent of cars in region South had studded tires in 2008 while the average for the rest of the country is close to 80 percent.

[6] Median life is the spot where the survival function $S(t) = 0.5$. The hazard function $h(t)$, which is estimated, is directly related to the survival function since $h(t) = -dlnS(t)/dt$.

Table 4: Lifetimes estimated from the Weibull model

Region	Surface	ADT cars	ADT ESAL	Median life (years)
M	Cold	344	22	16,7
M	Surface dressing	452	36	17,2
M	Hot	1317	104	16,2
N	Cold	329	36	17,8
N	Surface dressing	242	26	20,8
N	Hot	1246	111	17,9
Sthlm	Cold	283	12	15,7
Sthlm	Surface dressing	490	27	15,2
Sthlm	Hot	4846	216	11,5
S	Cold	271	11	19,2
S	Surface dressing	286	13	20,8
S	Hot	1479	98	16,9
V	Cold	339	15	18,5
V	Surface dressing	486	25	18,8
V	Hot	2592	206	15,1
E	Cold	278	12	16,2
E	Surface dressing	372	17	16,7
E	Hot	2063	135	13,5
Average		2280	143	17,0

5 Calculating marginal costs

Equation (4), for convenience reproduced below, is used for estimating marginal costs. In order to elaborate on the logic of the estimations, the equation is used for describing how the national average is calculated.

$$E[\frac{\partial PVC}{\partial Q}] = -\varepsilon \frac{C}{E[T]\bar{Q}_I} \frac{r}{\left(1-e^{-r\bar{T}}\right)} \int_0^{\infty} e^{-rv-\gamma v^{\alpha}} dv \qquad (4)$$

C is the construction cost. Table 2 demonstrated that the cost is SEK 87 per square meter for an average road. $\bar{Q}$ is the average annual traffic over the roads' life cycle. The 2012 figure is

2280 cars and 143 ESAL per average day. The pavement lasts for an average 17 years ($\overline{T}$). Since car traffic has increased by 1 percent p.a., it is straightforward to establish that over the period there are 2112 cars per average day.[7] With traffic growth at 1.8 percent p.a. for heavy vehicles, the number of ESALs is 125 vehicles per average day over the life cycle. The average number of heavy vehicles and cars using the average road between its birth and death is therefore (17 years * 365 days * 125=) 776 000 ESALs and (17 years * 365 days * 2112=) 13.1 million cars. The average cost is SEK 87 divided by these numbers, i.e. SEK 1,12 * 10^{-4} per ESAL and 6.64*10^{-6} per car.

The first component of eq. (4), ε, represents the deterioration elasticity, now split in two, i.e. $\hat{\varepsilon}_{cars}$ and $\hat{\varepsilon}_{ESAL}$. The numbers in table 3 indicate that increasing ESAL or number of cars by 10 percent will reduce the service life of pavements by about one percent for each. Multiplying the average cost by the respective elasticities, the result is (0.0888*1,12 * 10^{-4} =) 9.95*10^{-6} for ESAL and (0,1036*6.64*10^{-6} =) 0,69*10^{-6} for cars.

The official discount rate for the transport sector, r, is 3.5 percent. With median life being 17 years, the value of $\frac{r}{\left(1-e^{-r\overline{T}}\right)}$ is 0.078. The final component of eq. (4) is the integral $\int_0^\infty e^{-rv-\gamma v^\alpha} dv$. This is a means for handling the fact that the external shock, i.e. the non-expected increase in traffic, could materialise at any point of time between the previous and the next date for renewal. The value of the integral for the average road is 12.5, and the combination of these two terms 0.976. Given eq. (4), the marginal cost estimate is (9.95*10^{-6} * 0.976 =) SEK 9.71*10^{-6} for each ESAL and (0.69*10^{-6} * 0.976 =) SEK 0.673*10^{-6} for each car.

This benchmark estimate of marginal costs calculated per square meter at the same time as the standard way to represent traffic is by vehicle km. The average Swedish road being 6.75 m wide, and multiplying by 1 000 for consistence, the marginal cost for a heavy vehicle using an average road is therefore (6.75 * 1 000 * 9.71*10^{-6} =) SEK 0.066 per ESAL km for heavy vehicles and (6.75 * 1 000 * 0.673*10^{-6}=) SEK 0.0052 per km for cars.

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[7] $y*1{,}01^{16}=2280$ => y=1944, => (2280+1944)/2)

This numerical example is based on an average vehicle using an average road. A detailed calculation of marginal costs is, however, based on about 250 000 observations, one for each road section. In this, all road sections are given a weight based on length relative to total road length in order to create the total average. This is the approach used to derive all values in table 5. Comparing the last row in table 5 with the manual average calculated in the above example, it is obvious that the values in the table is much higher. The reason is that these numbers provides a better accuracy, accounting for actual road length rather than (implicitly) assuming all links to be equally long.

Table 5: Marginal cost, SEK per ESAL kilometre and SEK per car kilometre.

	ESAL	**Car**
M, Cold	1,13	0,069
M, S.D	0,21	0,014
M, Hot	0,99	0,190
N, Cold	1,12	0,093
N, S.D	0,20	0,020
N, Hot	0,50	0,033
Sthlm, Cold	1,04	0,044
Sthlm; S.D.	0,23	0,011
Sthlm, Hot	1,04	0,095
S, Cold	1,72	0,069
S, S.D	0,58	0,023
S, Hot	0,63	0,024
V, Cold	0,78	0,039
V, S.D	0,24	0,012
V, Hot	0,33	0,025
E, Cold	1,05	0,044
E, S.D	0,23	0,012
E, Hot	0,85	0,034
All	0,71	0,047

The only point of reference that can be used for these results is Haraldsson (2007); his estimates are SEK 0.01 for heavy vehicles and 0,001 for cars.[8] This means that our estimates are higher than before. One reason may be that heavy traffic is here transformed from number of vehicles to ESAL, which was not the case in the previous study. Another difference is that elasticities are now -0,09 and -0,10 while they were -0,04 and -0,052 in Haraldsson (2007) for heavy and light vehicles, respectively, i.e. they are now twice as large.[9] Moreover, we use more than twice the number of observations. Finally, although both studies are based on information from the same source, seven more years of observations are now available. We have seen in other, similar studies that there may be a change in maintenance methods during these years that may have consequences for elasticity estimates. It would require further analyses in order to sort out these differences.

6. Summary

The present paper has estimated the marginal costs for road reinvestment using information at a very disaggregate level. One robust result of the analysis is that not only heavy but also light vehicles affect the periodicity of pavement activities. Most probably, this is the consequence of the use of studded tires in this part of the world.

The impact of heavy vehicles on road standard varies across the country and in particular with respect to the type of pavement used. It is demonstrated that the cost for using roads with (cheap) surface dressing (S.D.) in not an indication of that heavy vehicles should be induced to use these roads. Rather, and referring back to the complex interactions depicted by figure 1, it provides an image of how the design decision to use low-cost pavements on roads not used by many (heavy) vehicles, by and large may trade off life cycle costs in an appropriate way.

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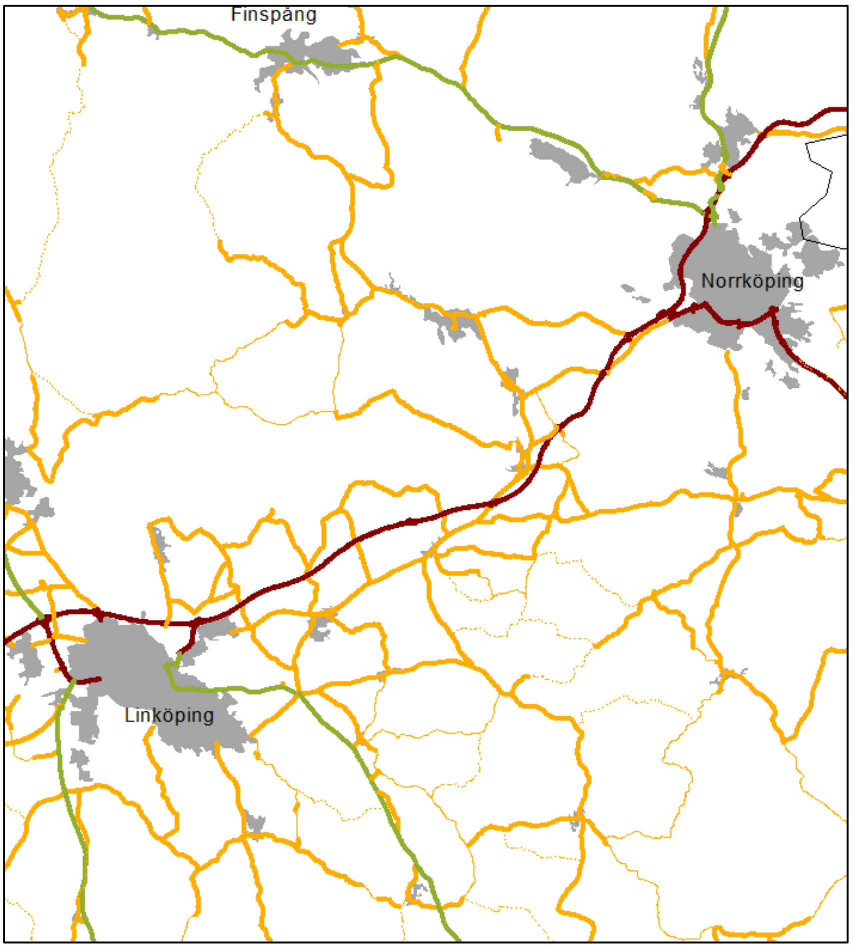
[8] The costs used in Haraldsson (2007) is based on a reference from 2004. Assuming that the cost per m2, which is SEK 65, refers to year 2000, and using CPI, the corresponding number for 2012, which is the year used here, is SEK 78. Since the cost for asphalt has increased much faster than consumer prices this compares well with the value used here, i.e. SEK 85 per m^2.

[9] The covariates in the respective equations are, however, not the same.

The use of disaggregate data also makes it possible to map result in the way illustrated by figure 4. The most striking observation is that the thickness of the lines/roads does not vary very much between roads in brown, green and yellow. This indicates that marginal costs are at a similar level even though traffic on roads with most traffic – the brown Europe roads – is much larger than on other roads. One explanation is provided by table 4, demonstrating that the spread around the national average road life length, 17 years, is low.



Europe road	Brown
National road	Green
District roads	Yellow

Figure 4: National roads around two cities in mid-Sweden. The breadth of a line indicates the marginal cost for wear and tear, with thin roads indicating low costs.

All analytical results refer to an average heavy vehicle. Using Table 2 however indicated that it is straightforward to generalize results using the ratios in the table in order to estimate costs for each type of vehicle.

Available data come with two major shortcomings. The first concerns the average cost statistic that only is based on three types of pavement. With more detailed cost estimates for pavement types, it may be feasible to further differentiate costs across different parts of the network. The second challenge emanates from the poor knowledge of actual weight and axle configuration of vehicles. More precise information would provide a higher degree of precision in the estimation of costs across the network.

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