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Annex A2
Deliverable 10: Infrastructure Cost Case Studies

Marginal cost of road maintenance for heavy goods vehicles on Swedish roads

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Abstract
The major component of road maintenance cost is the periodic renewal of the pavement. A new overlay is required every tenth or fifteens year. The length of the interval will depend on the traffic load measured as standard axles. The shortening of the intervals due to more traffic will change the present value of the maintenance cost. From this insight, an expression of the marginal cost related to HGVs is derived. It is shown that this marginal cost is equal to the product of the average cost and an elasticity that describes the change in lifetime due to more HGVs. Based on data from a Swedish long term pavement performance programme this elasticity is estimated and the marginal cost related to road wear and tear on Swedish roads are presented.

1 Introduction

The short-run marginal cost in relation to road wear and tear consists in principle of *two* components; the road authority's maintenance cost and the users discomfort and vehicle operating cost.

In this paper, the marginal maintenance cost is at focus. Moreover, of the maintenance cost, we only examine the cost of a new overlay that is required after a pavement has deteriorated to a too low standard. This cost component is difficult to estimate with ordinary econometric studies and we instead propose an alternative method.

The remaining maintenance costs includes winter maintenance, traffic signs, road markings, grass and hedge cutting, sweeping and cleaning, drainage etc. Some of these components may indeed also be relevant as a basis for marginal cost estimates. However, to estimate this kind of marginal cost, a more econometric approach has to be taken, and these costs are not included in the present paper.

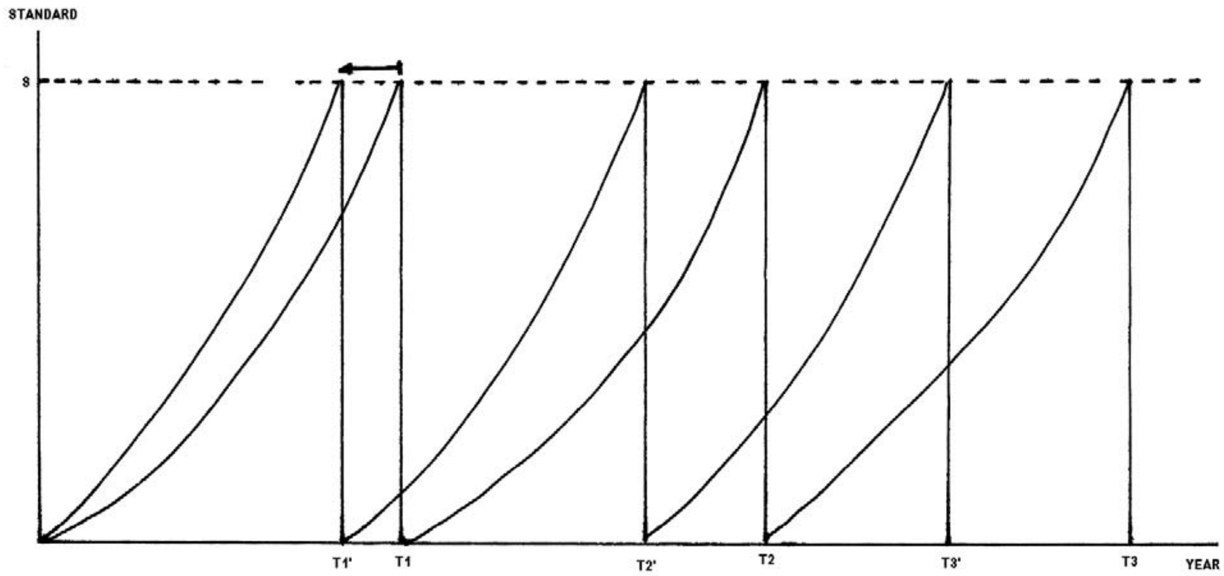
The pavement is designed to withstand a certain number of 'standard axles' after which a major roadwork has to be done. The pavement of a certain road is designed with this in mind, i.e. a given overlay will last for a certain number of years given a predicted flow of (future) traffic. If more 'standard axles' passes the road, the period between these overlays will be reduced. The shortening of the period is associated with a cost; this is the marginal cost of road wear.

In section 2 below, we develop the economic principles of marginal cost based on periodic overlays. Section 3 presents result of a Swedish study of road deterioration and a 'deterioration elasticity' is derived. In section 4 the marginal cost on Swedish roads are presented while section 5 contains a discussion and section 6 offers some conclusions.

2 The marginal cost of periodic overlays

A new road will be maintained to accommodate traffic over a number of years. The major work to renew the pavement will take place with certain intervals, most often between 10 and 20 years. The cost of these overlays can be expressed as a present value over an infinite horizon. This is a cost for road authority in order to keep the road open for traffic. *If the intervals between the overlays are constant, and the cost per square meter pavement are unaffected by traffic volume, this cost is not a short-run marginal cost that should be charged the road user.* However, whenever increased traffic will change this present value due to shortening of the intervals, a pricing relevant marginal cost arises.

Figure 2-1: Principle of marginal cost of periodic overlays



An overlay is made when the road has deteriorated to a pre-specified level (S). The road is designed with a certain schedule of overlays with the periods T1, T2, T3 etc. When the number of 'standard axles' increases, the road will deteriorate quicker to the pre-specified level (S). The period between the overlays will be shortened to T1', T2', T3, etc. The present value of the cost of the future overlays will increase and this increased cost in relation to the increased number of 'standard axles' is the relevant marginal cost.

The first intuition may be that this marginal cost can only be a small fraction of the maintenance cost. However, studies have shown that in many cases the marginal cost is equal to the average cost[1].

In the following, we first develop the present value for an average road (section 2.1) which is the base for the presentation of the theory for the marginal cost (2.2).

2.1 Present value

Let Θ be the number of 'standard axles' that can pass the road before the pavement has to be renewed. Assume also that a (predicted) constant stream of **Q** 'standard axles' pass the road each year. It has previously (Newbery (1988)) been assumed that Θ is a design parameter when the road is constructed and independent of the traffic volume. However, new studies (Wågberg (2001)) suggests that Θ is not constant, but a function of **Q**. This new empirical knowledge is included in the theoretical presentation below.

The pavement may also be affected by ageing where **m** is the annual increase in roughness due to the climate. The lifetime (**T**) of a pavement can be written[2]:

---

[1] Newbery, (1988), (1989), Small et.al. (1989)
[2] Based on Small et. al. (1989).

(1) $$T = \left[\frac{\Theta(Q)}{Q} \right] e^{-mT}$$

where:
T = period between the overlays
Θ = number of 'standard axles' the pavement can accommodate
Q = annual traffic volume measured as 'standard axles'
m = climate dependent deterioration

Each of the overlays has a cost of **C.** The first overlay take place at year 0 and the present value (**PVC_o**) of an infinite number of overlays can be written as (2) where **r** is the interest rate. If we examine a road in use year **t**, the next overlay will take place **T-t** years ahead. Consequently, the present value (**PVC_t**) will depend on the time left, until next overlay (3).

(2) $$PVC_o = C(1 + e^{-rT} + e^{-r2T} \ldots + e^{-rnT}) \qquad \lim_{n\to\infty} PVC_o = \frac{C}{(1 - e^{-rT})}$$

(3) $$PVC_t = e^{-r(T-t)} \frac{C}{(1 - e^{-rT})}$$

where:
C = Cost of an overlay
r = interest rate

We explore the present value for roads with different ages based on equation 3. For a new road (**t**=0), the pavement on the road is sunk cost; the next overlay will occur T year ahead, and the present value of all future overlays can be written as (4). For an old road near the time of necessary resurfacing (**t**=**T**), the present value is equal to (2) above. Finally, we derive an average present value for a road system where a number of segments have different age and where the age is equally distributed (5)[3].

Table 2-1: Present value of new overlays

(2) Old road	*(4) New road*	*(5) Average road*
$PVC_{Old} = \frac{C}{(1 - e^{-rT})}$	$PVC_{New} = \frac{C}{(e^{rT} - 1)}$	$PVC_{Average} = \frac{1}{T} \int_0^T e^{-r(T-t)} dt \frac{C}{(1 - e^{-rT})}$

We study the effect of annual traffic on the cost, and we will therefore examine the properties of the annualised present value (**ANC**), which for an average road can be expressed as (6).

(6) $$ANC_{Average} = r\, PVC_{Average} = \frac{C}{T}$$

3 This is simple the integral of the present values of all roads of different ages, from age t=0 to t=T, divided by T, which gives the average road.

2.2 The marginal cost

To simplify the theoretical presentation we assume that the whether has no influence on the deterioration (**m**=0). This assumption is supported by the empirical results presented in section 3.

Differentiating the annualised cost (**ANC**) with the annual traffic volume (**Q**) gives the marginal cost per 'standard axle'. This can be expressed for a new road (7) or an average road (8). It can be shown that the marginal cost for an old road is identical to the marginal cost for a new road[4].

Table 2-2: Marginal cost

(7) New road	*(8) Average road*
$MC_{New} = r\frac{dPVC_{New}}{dQ} = -r^2 e^{rT} \frac{C}{(e^{rT}-1)^2}\frac{dT}{dQ}$	$MC_{Average} = r\frac{dPVC_{Average}}{dQ} = -\frac{C}{T^2}\frac{dT}{dQ}$

Introducing a '*deterioration elasticity*' (**ε**) and an expression for the average cost **AC** the marginal cost for a new or old road (9) becomes a simple function of the average cost (**AC**), the elasticity (**ε**), a part (**α**) that depends on the interest rate (**r**) and the length of the pavement cycle (**T**). For the average road in a road network, where the age of the roads are evenly distributed, the marginal cost becomes even simpler, it is only a function of the average cost and the elasticity (10).

Table 2-3: Concluding Marginal cost

(9) New road or old road	*(10) Average road*
$MC_{New} = MC_{Old} = -(rT)^2 \frac{e^{rT}}{(e^{rT}-1)^2}\frac{C}{TQ}\varepsilon = -\alpha\,\varepsilon\,AC$	$MC_{Average} = -\varepsilon\,AC$

where:

$\varepsilon = \frac{dT}{dQ}\frac{Q}{T}$ Deterioration elasticity

$AC = \frac{C}{\theta} = \frac{C}{QT}$ Average cost

$\alpha = (rT)^2 \frac{e^{rT}}{(e^{rT}-1)^2}$

With a real interest rate of 4% the parameter α takes a value between –0.99 and -0.95 if the life cycle T is between 5 and 20 years. This is reduced to -1.00 to –0.97 if the interest rate is 3%. Consequently, *the marginal cost is approximately the same for an average road as for a new or old road.*

[4] $MC_{Old} = r\frac{dPVC_{Old}}{dQ} = -r^2 e^{-rT} C(1-e^{-rT})^{-2}\frac{dT}{dQ} = -r^2 e^{rT} C(e^{rT}-1)^{-2}\frac{dT}{dQ} = MC_{New}$

The value of the elasticity ε will determine the relationship between the average cost (**AC**) and the marginal cost (**MC**). If the road deteriorates only because of traffic, i.e. no weather effect, and the number of 'standard axles' the surface can withstand is constant, the elasticity becomes negative unity (11). The average cost (**AC**) is equal to the marginal cost (**MC**). This is what Newbery (1988) labelled the *Fundamental Theorem*. However, whenever ε takes some other value, the average and marginal costs will not be the same anymore.

(11) $$\mathrm{T} = \left[\frac{\theta}{Q}\right] \Rightarrow \varepsilon = -1 \Rightarrow MC_{Average} = AC$$

3 Pavement deterioration in Sweden

In the Swedish Long Term Pavement Performance (LTPP) project the deterioration of the pavement have been studied since 1985. Today the program consists of 639 road sections on 64 different roads. Most of the roads are located in south and the middle of Sweden.

Every year a detailed distress survey, measurements of rut depth and the longitudinal profile have been carried out at each section. The collected database contains information about structural strength, surface condition, pavement structure, climate and traffic.

Information on the road substructure is collected from the constructional drawing. In the sample, the most frequent base is between 0.60 and 0.75 meter with pavement thickness between 60 and 140 mm. The strength of the road is measured as Surface Curvature Index (SCI_{300})[5], where a drop weight is used. A lower value on SCI_{300} indicates a stronger construction.

(12) $$SCI_{300} = d0 - d300$$

where:

d0 = deflection in centre, μm
d300 = deflection 300mm from centre, μm

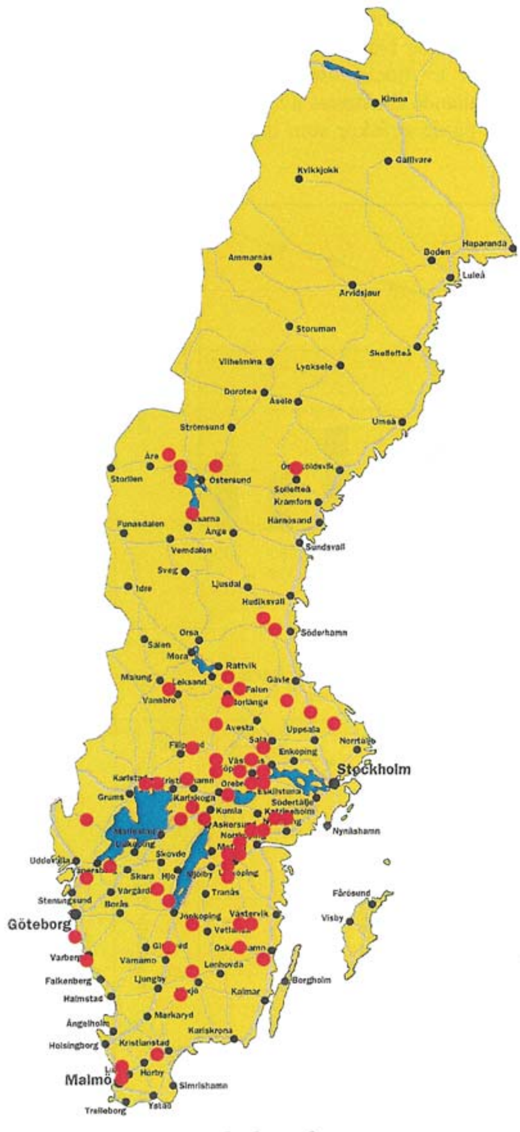
The pavement structure is measured with a laser-equipped vehicle and both length and cross profile are registered every 10 cm. Cracking in the wheel path is recorded manually based on clear guidelines (Wågberg, (1991)) by one of three road engineers. Traffic is measured as AADT and annual standard axles (**Q**). Climate is recorded both as rain and snowfall and as coldness in 'negative day degrees' (Celsius).

Table 3-1: Basic data for road sections

	Mean	*Std.Dev.*	*Minimum*	*Maximum*	*NumCases*
SCI300	137.341	43.9489	55.5224	293.845	386
VEHICLES	3951.3	2472.76	370	10900	386
Q	421.215	373.113	67	1320	386
WIDTH (m)[6]	10.6088	3.40604	7.5	20	386

[5] Deflection (how the pavement is compressed) is measured 300 mm from the centre
[6] Motorway = 20m

Figure 3-1: Roads and road segments in the Swedish LTPP project[7]



Län	Väg	Objekt	Antal
C	292	Gimo	9
C	E4	Månkarbo	10
D	20	Eskilstuna	14
D	53	Kvicksund	18
D	53	Nyköping	10
E	34	Brokind	16
E	E4	Herrbeta	17
E	1173	Rejmyre	9
E	34	Skeda Udde	15
E	34	Skeda Udde	1
E	215/1153	Skärblacka	6
E	36	Tift	12
E	55	Åby	7
F	195	Bankeryd	13
F	31	Nässjö	11
F	E4	Värnamo	21
F	E4	Värnamo	8
G	126	Moheda	11
G	23	Älmhult	11
H	33	Ankarsrum	10
H	34	Målilla	10
H	E22	Oskarshamn	11
H	33	Vimmerby	12
L	E22	Linderöd	12
M	103	Lund	6
M	11	Staffanstorp	9
N	E6	Frillesås	14
N	E6	Tvååker	10
P	166	Dals Ed	6
P	45	Lilla Edet	12
P	46	Trädet	9
R	44	Grästorp	10
R	E20	Hova	8
S	E18	Karlstad	13
S	E18	Kristinehamn	10
S	63	Saxån	14
T	50	Askersund	6
T	207	Hjälmarsberg	11
T	205	Laxå	8
T	205	Gälleråsen	10
T	60	Lindesberg	10
T	68	Lindesberg	11
U	252	Hallstahammar	9
U	53	Kvicksund	11
U	580	Köping	8
U	67	Sala	10
W	80	Bjursås	10
W	60	Borlänge	1
W	60	Borlänge	10
W	60	Borlänge	1
W	850	Falun	1
W	60	Ludvika	10
W	880	Svärdsjö	1
W	266	Sörbo	12
W	71	Äppelbo	7
X	83	Arbrå	10
X	301	Bollnäs	13
X	67	Hedesunda	11
Y	90	Sollefteå	8
Z	675	Kaxås	12
Z	45	Lit	10
Z	321	Mattmar	12
Z	E14	Mattmar	10
Z	45	Svenstavik	11

We present the measure of crack initiation used in the LTPP project in section 3.1, the estimated function of lifetime is then presented (3.2) from which we develop the 'deterioration elasticity' (3.3).

3.1 Crack initiation

Crack initiation in the wheel path is an indication of deterioration caused by heavy vehicles. Within the LTPP project, a study on initiation of cracking for flexible pavements has been carried out. The modelling of crack initiation used a survival analysis approach (see Wågberg (2001)). From the data, describing the yearly development of cracks, a Cracking Index was calculated. The Cracking Index (S) is based on three elements; crackled surface (**Cr**),

[7] Source: Wågberg (2001)

longitudinal cracking (**LSpr**) and transverse cracking (**TSpr**). The degree of severity is defined in Wågberg (1991).

(13) $S = 2Cr(m) + LSpr(m) + TSpr\ (st)$

where:

$$Cr = Cr_{low}(m) + 1.5\ Cr_{middle}(m) + 2\ Cr_{severe}$$
$$LSpr = LSpr_{low}(m) + 1.5\ LSpr_{middle}(m) + 2\ LSpr_{severe}$$
$$TSpr = TSpr_{low}(m) + 1.5\ TSpr_{middle}(m) + 2\ TSpr_{severe}$$

A Cracking Index, S>5, is chosen as the terminal value. The dependent variable is the number of accumulated 'standard axles' that has passed the road section when the terminal value is reached. A number of different models have been tested with the independent variables listed in Table 3-2 (see Wågberg (2001)).

Table 3-2 Independent variables

Measure of:	*Name*	
Traffic	*AADT*	
	Standard axles per year	*(Q)*
	Proportion HGV	
Road construction	*Thickness of base and pavement*	
Strength	*Measured deflection*	
	Surface Curvature Index 300	*(SCI)*
	Tensile strength	
Age	*Year since construction*	
Climate	*Annual average coldness*	
	Annual accumulated coldness	
	Annual rain and snowfall	
	Annual accumulated rain and snowfall	

The chosen model in Wågberg (2001) turns out to be very simple. The accumulated number of standard axles when the terminal value is reached is a function of the initial strength (SCI), measured as SCI_{300}, and the number of annual 'standard axles' (**Q**) (14).

(14) $$\theta_{S>5} = 10^{\left\{7.24 - 0.0052 * S - 5010000 \frac{1}{SCI * Q}\right\}}$$

The model is restricted in the combination of allowed strength and number of standard axles. If the road is too strong in relation to traffic load, the deterioration is not a function of load anymore. The minimum strength is restricted to:

(15) $$SCI_{\min} = \sqrt{\frac{5010000}{0.0052Q}}$$

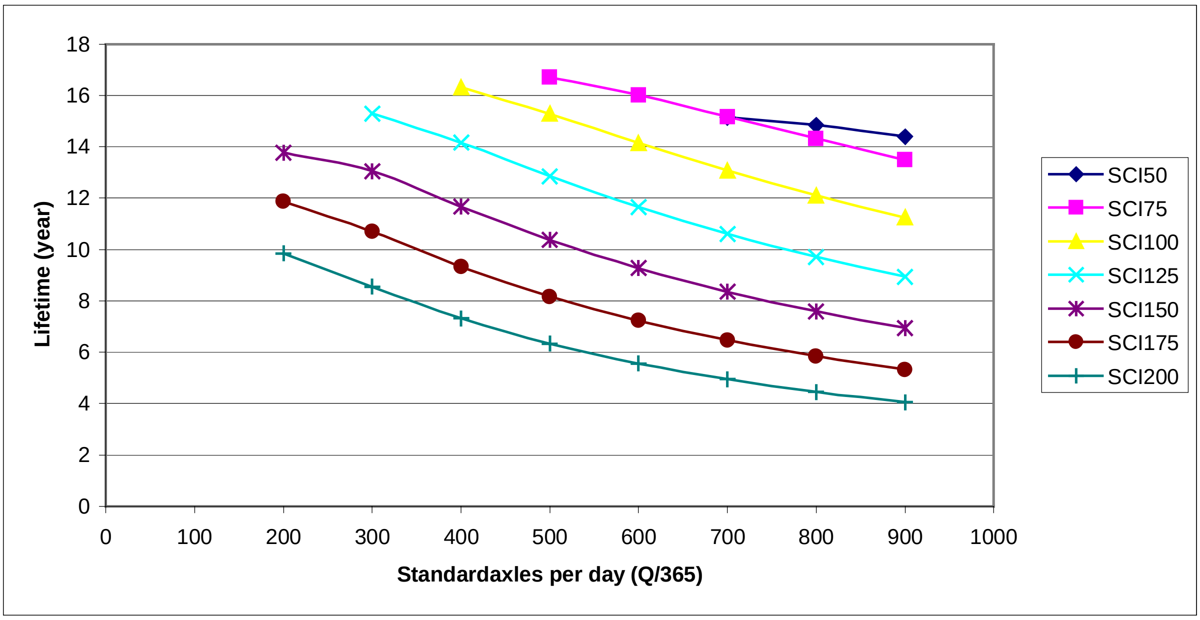
3.2 Lifetime of an overlay

We assume the pavement will be renewed when the terminal value of the Cracking Index is reached (S>5). The lifetime of a pavement is a function of the (constant) annual number of 'standard axles' that passes the road and the strength of the road (16).

(16) $$T_{S>5} = \frac{10^{\left\{7.24-0.0052*S-5010000\frac{1}{SCI*Q}\right\}}}{Q}$$

The figure below presents the result within the allowed combination of SCI and Q. The lifetime decreases with reduced strength (higher SCI) and increased traffic load (**Q**) as could be expected.

Figure 3-2: Predicted lifetime of a pavement (T) in relation to daily standard axles (Q/365).



3.3 Deterioration elasticity

The change in lifetime as the traffic increases is expressed as an elasticity (17), which follows simply from the expression of the lifetime (16). In Table 3-3 we present the elasticity within the reasonable combination of strength and traffic volume.

(17) $$\varepsilon = \frac{dlnT}{dlnQ} = -\left[Ln\left(-501000\frac{1}{SCI*Q}\right)\right]-1$$

Table 3-3: Deterioration Elasticity

Standard axles per day and direction (Q/365)	SCI						
	50	***75***	***100***	***125***	***150***	***175***	***200***
200	-	-	-	-	-	-	*-0,21*
300	-	-	-	-	*-0,30*	*-0,40*	*-0,47*
400	-	-	*-0,21*	*-0,37*	*-0,47*	*-0,55*	*-0,60*
500	-	-	*-0,37*	*-0,49*	*-0,58*	*-0,64*	*-0,68*
600	-	*-0,30*	*-0,47*	*-0,58*	*-0,65*	*-0,70*	*-0,74*
700	*-0,10*	*-0,40*	*-0,55*	*-0,64*	*-0,70*	*-0,74*	*-0,77*
800	*-0,21*	*-0,47*	*-0,60*	*-0,68*	*-0,74*	*-0,77*	*-0,80*
900	*-0,30*	*-0,53*	*-0,65*	*-0,72*	*-0,77*	*-0,80*	*-0,82*

- = not allowed combination

The elasticity varies from –0.1 on high quality roads with low traffic load up to –0.8 on low quality roads with high traffic load. *For a given traffic load the (negative) elasticity increases with reduced strength and for a given strength the (negative) elasticity increases with increased traffic.* This result is intuitive appealing, the highest marginal cost can be expected at low quality roads with high traffic volumes and the lowest cost at high quality roads with low traffic volumes.

4 The Marginal cost of heavy vehicles on Swedish roads

Based on the expression of the marginal cost in an average network without climate effect (equation 10 above) we can estimate the marginal cost related to ‘standard axles’ on roads with different strength and traffic load, based on the ‘deterioration elasticity’ presented above.

Section 4.1 presents information on the cost of an overlay (C) in Sweden, which, together with the elasticity, forms the base for the marginal cost per standard axle (4.2). This cost can be expressed per vehicle (4.3) if we know the number of standard axles per vehicle. The MC is finally expressed for all the roads in our sample (4.4).

4.1 Cost of an overlay

The annual road maintenance cost consists of a number of different categories; the main categories are *reconstruction and resurfacing cost*, bridges and remedial earthwork, winter maintenance and minor investments. Half of the cost is the cost related to reconstruction and resurfacing and the others have a cost of around 15% each.

The Swedish National Road Administration (*Vägverket*) has provided us with information on the *reconstruction and resurfacing cost* for roads with different traffic volume (total volume of vehicles, AADT) in different regions. The *reconstruction and resurfacing cost* includes cost for surface dressing, skid treatments, patching and minor repairs besides the cost for an overlay. The cost of an overlay consists of the cost of pavement, including work, and the cost of necessary repair[8] of the substructure. The proportion of overlay cost of the reported *reconstruction and resurfacing cost* is on average 58%. If *reconstruction and resurfacing cost* is half of the maintenance budget the overlay cost we consider is around 30% of the total maintenance cost including winter maintenance and minor investments.

While we are interested in the cost for an overlay, some of the other components may indeed also be relevant as a basis for marginal cost estimates. However, to estimate this kind of marginal cost, a more econometric approach has to be taken, and these costs are not included in the present paper.

The cost of an overlay per kilometre road is between 14 182 €/km on the narrow roads in the south up to 71 076 €/km on the wide roads in the north. The average cost is 24 803 €/km.

Table 4-1: Maintenance and overlay cost in Sweden

Traffic volume AADT	*Region*	*Average road width (m)*	*Road Length (km)*	*Reconstr. and resurf. cost (k€/km)*	*Overlay cost (k€/km)*	*Proportion overlay cost of total maintenance cost*
<500	South	6	20 767	2.6	14.2	0.50
	Middle	6	6 065	3.8	18.9	0.45
	North	6	10 056	4.5	19.7	0.40
500-2000	South	7	12 323	3.8	30.5	0.80
	Middle	7	5 020	4.8	30.9	0.64
	North	7	6 272	6.2	30.8	0.50
2000-8000	South	9.5	7 911	6.7	35.0	0.65
	Middle	9.5	2 873	7.2	34.8	0.57
	North	9.5	1 600	8.5	34.1	0.50
>8000	South	18	2 689	12.9	66.0	0.64
	Middle	18	658	13.5	67.8	0.63
	North	18	178	14.6	71.1	0.61

2001 prices. Exchange rate 8.92 SEK/€ Source: Johansson and Fredriksson (2001)

4.2 Marginal cost

Our approach lends itself to a high degree of differentiation. The marginal cost depends on the road strength, measured as SCI, the number of 'standard axles', and the cost of a new pavement. All of these variables vary between road sections and, consequently, the marginal cost can be expressed for each road section. In addition, our marginal cost is expressed *per standard axle*. This means that it easily can be expressed for different vehicle categories with different axle configurations.

In Table 4-2 below the marginal cost is presented for different traffic load and road strength. For a given traffic load of 700 standard axles per day (and direction) the marginal cost is around 0.07 € per 100 Standard Axle kilometre on high quality roads and the marginal cost increases to 1.62 €/100SAkm when the road strength is reduced.

[8] *Vägverket* estimates the cost of repair to be half of the overlay cost.

Table 4-2: Marginal cost per standard axle (SA) on Swedish roads with an average pavement cost (€/100SAkm)

Standard axles per day and direction(Q/365)	*SCI*						
	50	***75***	***100***	***125***	***150***	***175***	***200***
200	-	-	-	-	-	*0.29*	*0.76*
300	-	-	-	*0.25*	*0.54*	*0.89*	*1.32*
400	-	-	*0.23*	*0.47*	*0.73*	*1.05*	*1.48*
500	-	*0.13*	*0.34*	*0.55*	*0.80*	*1.12*	*1.55*
600	-	*0.22*	*0.40*	*0.59*	*0.84*	*1.15*	*1.58*
700	*0.07*	*0.27*	*0.43*	*0.62*	*0.86*	*1.17*	*1.60*
800	*0.13*	*0.30*	*0.45*	*0.63*	*0.87*	*1.19*	*1.61*
900	*0.16*	*0.31*	*0.46*	*0.64*	*0.88*	*1.19*	*1.62*

1 € = 8.92 SEK

It should be observed that the table above is based on the average cost of an overlay. It could be expected that roads with a higher SCI, i.e. lower standard, are minor roads with a lower cost of overlays.

4.3 Marginal Cost by Vehicle type on our sample of road sections

The cost per standard axle can be expressed as a cost per vehicle type. We have used information from *Vägverket* on standard axles per vehicle type (vehicle equivalent factor VEF) for four groups of goods vehicles.

An average road in our sample has a marginal cost of 0.80 €/100SAkm (see the section below). This means a marginal cost of 0.32 €/100vkm for the light duty vehicle (LDV) and 1.86 €/100vkm for the heaviest vehicles (HGV with trailer).

Table 4-3: Standard axles per vehicle (VEF) and Marginal cost by vehicle type

	VEF	*€100Vehkm*
LDV	0.4	*0.32*
LDV with trailer	0.85	*0.69*
HGV	0.96	*0.77*
HGV with trailer	2.3	*1.86*

4.4 Marginal cost for the sample of road sections

We do not have information on SCI and ‘standard axles’ for the complete Swedish road network. We can thus not make a reliable average of the marginal cost. However, behind our approach is an assumption that differentiation matter; to make an average is thus against our principles.

Instead, we use our data on almost 400 road sections where we have measured SCI and ‘standard axles’. Summary statistics is presented in Table 3-1 above. Not all of the sections fall within our restrictions on the combination of SCI and Q (equation 15). In the table below, we have restricted the dataset to only sections with the allowed combination. The mean SCI is lower and the mean number of 'standard axles' is higher compared to the complete dataset.

We allocate the overlay cost presented in Table 4-1 to each road section depending on the traffic volume (**AADT**) and region[9]. For each of the 249 road sections, we estimate lifetime, deterioration elasticity, average cost (**AC**), marginal cost (**MC**), and Cost recovery rate (MC/AC).

The average lifetime is estimated to 11.8 years and the elasticity to –0.43. The average cost per standard axle kilometre is 2.2 €/100SAkm and the marginal cost 0.80 €/SAkm. The cost recovery rate is 0.36.

Table 4-4: Basic information, average cost and marginal cost for the subsample

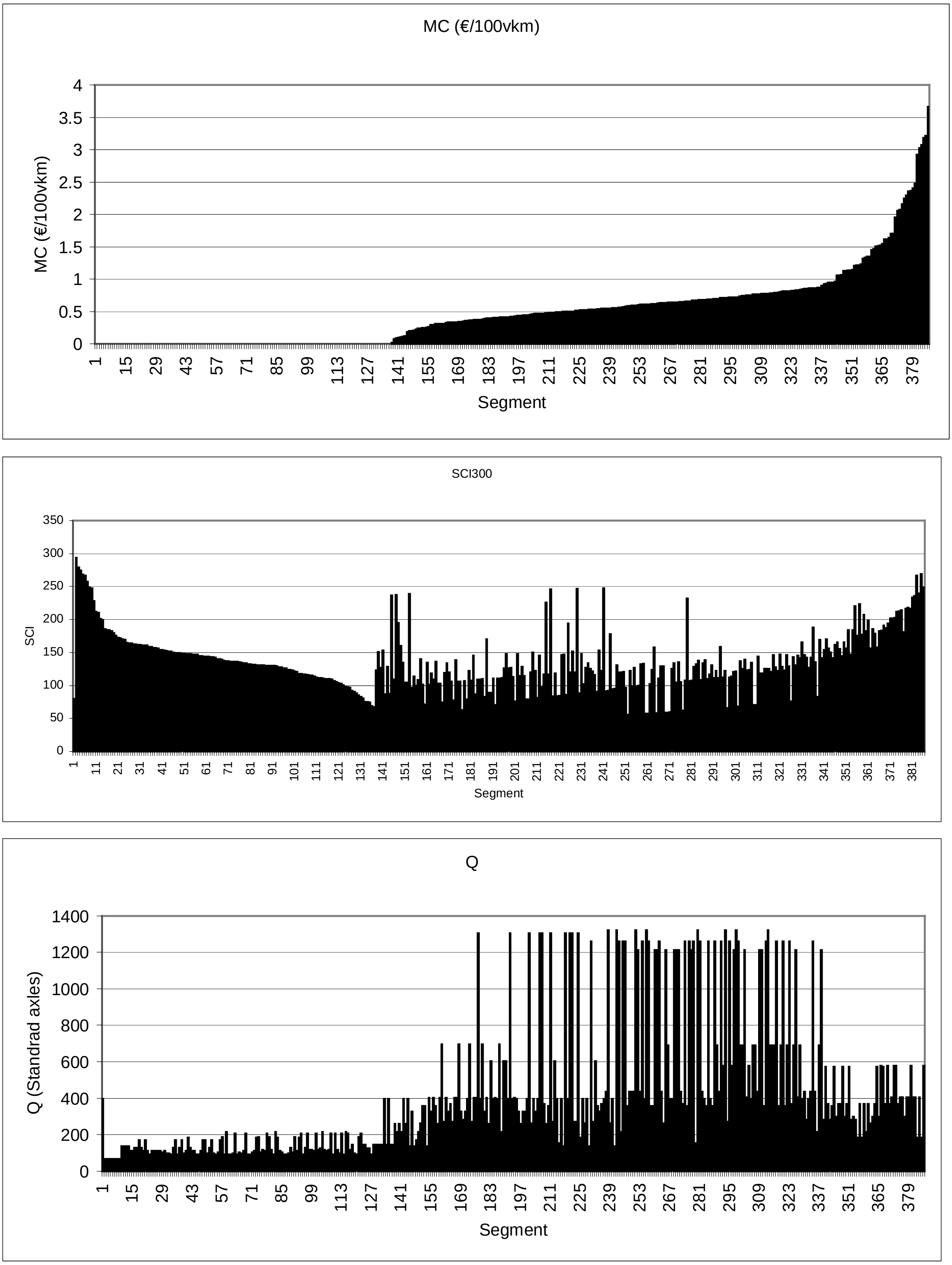
	Mean	*Std.Dev.*	*Minimum*	*Maximum*	*NumCases*
SCI	*133.997*	*44.3632*	*55.5224*	*269.104*	*249*
Vehicles (AADT)	*5131.57*	*2278*	*1290*	*10900*	*249*
WIDTH (m)	*11.7209*	*3.75126*	*7.5*	*20*	*249*
Q (per day and direction)	*578.94*	*379.485*	*137*	*1320*	*249*
OVERLAY COST (kSEK/km)	*37.0*	*8.7*	*30.5*	*66.0*	*249*
LIFETIME (year)	*11.8103*	*3.11661*	*3.36859*	*16.9688*	*249*
ELAST	*-0.431342*	*0.221295*	*-0.80211*	*-0.00908*	*249*
AC (SEK/SAkm)	*0.022*	*0.016*	*0.006*	*0.093*	*249*
MC (SEK/SAkm)	*0.008*	*0.0061*	*0.0002*	*0.038*	*249*

1 € = 8.92 SEK

Figure 3 below, presents in the first graph the marginal cost for HGV on all road segments (sorted by MC), the second graph shows the SCI for these segments and the last graph the number of standard axles. As can be expected, our model excludes roads with a high SCI and low traffic volume. On the roads where our model predicts the marginal cost, we can see that the cost increases strongly with increased SCI, i.e. reduced road strength.

[9] South=2, Vv region Skåne, Väst, Sydväst; Middle=1, Vv region Mälardalen, North=3, Vv region Mitt

Figure 3: Marginal cost for a HGV (€/100vkm) on all segments (zero on segments with not allowed combination), road strength (SCI) and standard axles (Q) on these segments.



5 Discussion

5.1 The road network is not evenly distributed

The assumption on an even age distribution of roads in the network simplifies the expression of the marginal cost (equation 10). However, we have also shown the expression of the marginal cost for a new and an old road (equation 9). The difference between the average and an old or new road depends on the parameter α. We have shown that with reasonable assumptions, this parameter takes a value not far from unity, and the costs are similar.

5.2 Other reasons to resurface the road

Crack initiation in the wheel path is not the only deterioration that may trigger a major roadwork. On roads with high traffic volume and a high proportion studded tyre rut depth become a serious problem.

Based on the long-term dataset we have analysed the roadwork *Vägverket* has done on each road. A roadwork is not restricted to a minor section but take place on a whole road; this means that we only have 64 roads in our sample. For 36 of these roads the road authority has undertaken a major roadwork.

The average lifetime of a pavement in the sample is 9.9 years. The maximum value on all sections in a road is expressed as the maximum Cracking Index (MaxS), maximum IRI (MaxIRI) and maximum rut depth (MaxRD). In 86% of the cases the Cracking Index is above 5 and in 47% of the cases is the rut depth above 17mm, which we assume is the trigger value. In 8% of the cases is none of these two criteria above a trigger value.

Table 5-1: Road standard when major roadwork is undertaken

	Mean	*Std.Dev.*	*Minimum*	*Maximum*	*NumCases*
LIFETIME	9.90259	3.48551	4.29315	19.1507	36
VEHICLE	4665	3093.2	670	12000	36
Q	434.247	386.78	35.0886	1948.72	36
MaxS	172.861	191.809	0	674.5	36
MaxIRI	1.84262	0.249786	1.48	2.6158	36
MaxRD	17.6393	6.12902	4.92	30.21	36
S>5	*0.861111*	*0.350736*	*0*	*1*	*36*
RD>17	*0.472222*	*0.506309*	*0*	*1*	*36*
NONE	*0.083333*	*0.280306*	*0*	*1*	*36*

The limited dataset allows us not to estimate a reliable model of the probability that the Cracking Index is the trigger for the decision on the roadwork. The only conclusion we can draw is that for 14% of the cases the Cracking Index is not above the trigger value. It can be argued that the marginal cost we have estimated should be reduced with the factor 0.86.

5.3 Non-optimal behaviour

The road authority may not respond with a new overlay when the trigger value has been reached due to budget constraints. However, if they still has a trigger value, although higher, the function developed for the marginal cost is still valid but new empirical data has to be used. The evidence from the LTPP project suggests that after the first trigger value has been passed, the road starts to deteriorate quicker, which indicates a higher elasticity and consequently a higher marginal cost.

5.4 Climate

The model is in this paper restricted to not include climate dependent deterioration because the empirical result from the LTPP project suggested that climate has no explanatory power. Nevertheless, we see that the restriction on the allowed intervals means that a number of roads fall outside the model. This is especially true for roads with low traffic load; roads where we can expect the climate to have a higher impact. Traffic growth is neither included in the model but can easily be done.

5.5 Comparison with the Cost Allocation method

Vägverket (2001) presents an estimate on the ‘marginal cost’. The method was a cost allocation method where the maintenance cost was split into variable and fixed costs. The variable cost was split into cost depending on passenger cars and HGVs. These cost where then expressed as a cost per standard axle kilometre. The average cost was 1.29 €/100Sakm (see Table 5-2 below).

Our method only covers the cost related to a new overlay, which is only a fraction (30%) of the total maintenance budget. Exactly how *Vägverket* has treated this cost component in their study is not clear. They have assumed 34% of the maintenance cost to be variable costs of which 62% are related to HGV, which means that they allocate 21% of the maintenance budget to HGV.

We have summarised the marginal cost estimated in our sample, presented in the section above, by traffic category in the last column of Table 5-2. We do not have information for the lowest traffic category (<500), which is the largest group of roads with respect to road length. To compare the average of the cost allocation method with the average in our sample is thus not meaningful.

However, we can compare the cost estimated for the other traffic categories. For roads with an AADT of 500-2000 our estimate is 31% of the estimate with the cost allocation method, for the next category our estimate is 24% and for the category with AADT above 8000 our estimate is 23% of the result from the cost allocation method employed by *Vägverket*.

The estimates are not comparable, as our estimate only covers the reconstruction and resurfacing cost and *Vägverket* does include all costs.

Table 5-2: Cost allocation model

Traffic category	*Maintenance Cost (M€ /year)*	*Proportion variable cost (%)*	*Variable Maint.Cost (M€ /year)*	*Allocated to HGV (%)*	*Road length (km)*	*AADT*	*Proportion HGV (%)*	*Cost per SA km (€ /100Sakm)*	*Marginal cost from our sample (€ /100Sakm)*
<500	90.2	10	9.1	80	36033	200	5	0.68	
500-2000	89.9	30	27.0	70	23717	1000	5	1.05	*0.32*
2000-8000	75.4	50	37.8	60	14125	4000	8	3.35	*0.82*
>8000	37.7	70	26.3	50	3202	9000	14	4.23	*0.97*
Total	**293.4**	**34**	**100.1**	**62**	**-**	**-**	**Average**	**1.29**	***0.80***

Source: Vägverket 2000. VEF=1.3

5.6 Generalisation

The method is easy to generalise to other countries. Developments of methods to estimate the lifetime of pavements has been carried out in research projects financed by the European Commission (PARIS project) and the basic information should be available for a number of European countries.

6 Conclusion

We have shown how the periodic overlay should be handled in estimates of the marginal cost of road use. The theory is not new and draws heavily on work done in the 80's, although we have expanded the theory and include a 'deterioration elasticity'. While the theory presented here is restricted in some dimensions, it is no problem to include climate dependent deterioration or traffic growth in the model. In our version, the marginal cost becomes a simple function of the average cost and the 'deterioration elasticity' (MC= -ε AC).

Based on work done in the Swedish Long Term Pavement Performance project we have calculated a 'deterioration elasticity', which shows how the periods between overlays will change as the traffic increase, or more precise, as the number of standard axles increases. The elasticity depends on the traffic load in standard axles and the quality of the road. The elasticity is –0.1 on high quality roads and –0.8 on low quality roads with a high load of standard axles. In no situation will a marginal cost based charge ensure full recovery of the overlay cost.

With information on the cost of an overlay in Sweden, we can estimate the marginal cost for roads of different quality and traffic load. The marginal cost will vary from 0.065 €/100Sakm, i.e. per 100 standard axle kilometre, on high quality roads up to 1.62 €/100SAkm on low quality roads (see Table 4-2) (even higher costs can be found if lower road quality is assumed). Some persons hold the position that it is impossible to ask the user to pay such a higher price on bad roads. However, this result exactly mirrors the practice of the Swedish National Road Administration to restrict the use of low quality roads for the heaviest trucks, especially at the taw period.

The approach lends itself to a high degree of differentiation and the result can easily be expressed per vehicle kilometre for a certain combination. As an example in the paper, we use an average Swedish HGV without trailer and shows that the marginal cost vary from 0.08 €/100vkm on high quality roads in our sample up to 3.7 €/100vkm on a few very bad roads in the sample.

While the approach is promising, we should in the future examine the behaviour of the Road Authority. In our sample, our Cracking Index was above the trigger value in 86% of the cases where the Road Authority had made a new overlay. However, at the same time the rut depth was serious in some cases, which raises the question if the HGV created cracks drives the need for the overlay, or other factors. In addition, we do not have data on the road quality, or even annual number of standard axles, for the whole network.

The method is easy to generalise to other countries. Developments of methods to estimate the lifetime of pavements has been carried out in research projects financed by the European Commission (PARIS project) and the basic information should be available for a number of European countries.

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