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## Winter tyres – Traffic safety

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Reprint from conference proceedings, Winter Cities 2004,  
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## **Preface**

Enclosed papers were presented at the Winter Cities Anchorage 04 Conference in Anchorage, Alaska, 18–22 February 2004.

We want to acknowledge and give credits to Winter Cities Anchorage 04, Municipality of Anchorage and International Association of Mayors of Northern Cities for a successfully accomplished conference as well as for kind permission to reprint our papers.

Linköping, Sweden, May 2005

*Gudrun Öberg*



## **Prediction models for pavement wear and associated costs**

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## Background

Prediction models that describe changes in the condition of various portions of a road structure constitute a valuable tool for evaluating the service life and economics of a road structure or of a surfacing measure. Prediction models also constitute the core of planning systems—Pavement Management Systems—which are based on changes in the condition of various road structures and asphalt layers depending on traffic and time. The prediction model discussed in this report describes the magnitude of wear of pavement and of rut formation created by vehicles with studded tyres. The work on this model was carried out as part of a project financed by the Swedish Transport and Communications Research Board (KFB) and the Swedish National Road Administration. The model is based on the results and experiences gathered during the last ten years of work at VTI (the Swedish National Road and Transport Research Institute), with the objective of developing and evaluating the wear resistance of asphalt wearing courses.

## Objective

The objective was to develop a computer based prediction model for the rut formation that is caused by wear from studded tires. The model shall both provide a prediction of the wear resistance of the wearing course based on data regarding the type of wearing course, the properties of component materials, and a model of the rut profile based on data for type of road, traffic load, etc. In the first stage, the model is limited to include wearing courses of type *ABT (dense-graded asphalt concrete)* and *ABS (stone matrix asphalt)*. However, these two types of wearing courses are by far the most common road surfaces on high traffic roads in Sweden.

## Expected use

The model can be a helpful tool for the following tasks:

- Support for decisions based on technology and economics in the choice of wearing courses, quality requirements for aggregates etc. for individual projects.
- Evaluation of the technical/economic effects on road infrastructure depending on what strategy is selected regarding interventions.
- Calculation of service life until the next measure. Since the model is intended to be used to evaluate a road's service life up to maximum permitted rut depth, it could also serve as an aid for planning and assigning priority to different road surfacing measures.
- Planning and control of the lateral positioning of traffic. On road sections where traffic is confined to the ruts created by studded tires, it is possible to extend the service life of pavements by moving the lane marking lines and thereby alter the lateral position of traffic.
- Calculation of annual costs caused by wear from studded tires. By entering data for the price of materials, the model can assist in evaluating whether it pays to purchase and transport high quality stone material instead of using cheaper mineral aggregate available locally.
- A pedagogical tool to disseminate knowledge about how various factors affect the magnitude of wear and its dispersal across the width of the traffic lane.

## **Description of the prediction model**

The prediction model consists mainly of three parts:

- A model that calculates the magnitude of wear per number of vehicles with studded tires.
- A model that calculates how the wear is distributed across the width of the driving lane (wear profile).
- A model that calculates, for example, annual costs based on materials used and estimated service life.

### ***Partial model for predicting the magnitude of wear***

The partial model, which calculates the magnitude of wear per number of vehicles with studded tires, is based on a large amount of wear data from the last ten years of research and development at VTI. Most of the data comes from pavement slabs that were placed both in existing pavements on high traffic roads and in VTI's Road Simulator. The slabs of bituminous represent different types of surfacing, a variety of aggregate properties, different aggregate sizes, etc.

All tests done in the Road Simulator used ABT16 with a porphyry mineral aggregate from the same exact source in Älvdalen. Wear on other pavement slabs was therefore related to this reference pavement, which was given the reference value of 1.0.

A database was constructed containing the pavement data for all the pavement slabs, which could be considered relevant in this context on the basis of previously made experiences. The following pavement data are included in the database:

- |  |  |
|--|--|
| • Type of pavement (ABT, ABS)          | • Type of aggregate and fraction, respectively |
| • Type of binder                       | • Largest aggregate size                       |
| • Binder content                       | • Aggregate grading                            |
| • Fibre additive, if present           | • Content of coarse aggregate                  |
| • Bulk density                         | • Flakiness index                              |
| • Aggregate density                    | • Impact value                                 |
| • Air void ratio according to Marshall | • Abrasion value                               |
| • Degree of compaction                 | • Ball mill value                              |

Wear data from test drives in the Road Simulator are in the form of three measured profile lines per pavement slab. The profile was measured prior to testing (zero measurement) and at regular intervals during the test, which means profiles at 5000, 15000, 25000, 45000, 65000, 85000, 105000, 125000, 245000 and 305000 revolutions (final measurement). The wear profile is calculated by subtracting the profile lines from each measurement occasion from the zero profile before testing, whereupon average wear for each profile line and pavement slab is calculated.

On pavement slabs that were placed in wearing courses on roads with traffic, a so called zero measurement was taken in the autumn prior to the studded tire season and a final measurement at the end of the studded tire season. Average wear for

each profile line and pavement slab was calculated in the same manner as for the Road Simulator. The number of vehicles with studded tires that passed the pavement slabs was measured and calculated so that the magnitude of wear could be related to the number of passes with studded tires.

The development of the model was based on a stepwise multiple linear regression analysis, which is a method that is normally used to develop this type of model. The software used for the model development work was SPSS 7.0 for Windows.

After careful examination of the relevance of all the data, work on the model was begun with an analysis of the correlation coefficients between relative wear and the variables that could be included in the model.

### *Correlation coefficients*

	<b>Air void ratio</b>	<b>Degree of compaction</b>	<b>Largest aggregate size</b>	<b>Ball mill value</b>	<b>Optimum Stone content</b>	<b>Aggreg. content &gt; 4 mm</b>	<b>Aggreg. content &gt; 8 mm</b>
<b>Relative wear, ABT + ABS</b>	-0.035	-0.088	-0.458	0.731**	-0.267*	-0.336**	-0.425**
<b>Relative wear, ABT</b>	-0.039	-0.034	-0.544**	0.823**	-0.585**	-0.528**	-0.578**
<b>Relative wear, ABS</b>	0.125	-0.221	-0.540**	0.730**	-0.013	-0.333**	-0.369**

\* *The correlation is significant at level 0.05 (2-tailed)*

\*\* *The correlation is significant at level 0.01 (2-tailed)*

The correlation coefficient was analysed for three different cases: ABT and ABS together, and individually for ABT and ABS.

As shown by the correlation coefficients in the above table, the correlation is strongest between relative wear and the ball mill value of the coarse aggregate fraction, the various measurements for the content of coarse aggregate and for the largest aggregate size.

The reason why the correlation coefficient is low between relative wear and degree of compaction and air void ratio, respectively, is that the variation in the degree of compaction and air void ratio is small in the laboratory manufactured slabs, where the air void ratio and compaction degree were consciously put at a low and high level respectively. When the degree of compaction was too low, the slabs were not approved and they were discarded. Had a greater variation in air void ratio and degree of compaction been permitted, these variables would, in all probability, have exhibited a strong correlation with wear. A low degree of compaction could, in the long term, lead to deterioration of properties such as resistance to ageing and durability.

The regression equation was calculated with the aid of a stepwise multiple linear regression analysis with the expression for relative wears as the dependent variable. The calculations were done with some different prerequisites. A regression equation was calculated both for ABT and ABS together, and also for each separate type of pavement. The reason for this procedure was that the pavement types are quite different and therefore it is not given that one and the same calculation model would be equally good for both types of pavement. Furthermore, the regression analysis was done using various expressions for aggregate content, namely optimum stone content (the content of stone material in the particle size immediately below the largest nominal stone size) as well as the content of stone >4 mm and > 8 mm, respectively.

The calculated correlation coefficients (R), the coefficient of determination (R<sup>2</sup>) and the regression equations for the various calculation alternatives are shown in the table below.

*Correlation coefficients, coefficient of determination and regression equations*

<b>Optimum Aggreg. content</b>	R	R <sup>2</sup>	Regression equation
ABT & ABS	0.85	0.71	$S=2.035+KV*0.144-MS*0.073-OPTH*0.0011$
ABT	0.93	0.84	$S=0.805+KV*0.161-OPTH*0.03+HM*0.316$
ABS	0.85	0.71	$S=1.547+KV*0.143-MS*0.087$
<b>Aggreg. content &gt;4 and &gt;8 mm, respectively</b>			
ABT & ABS	0.86	0.73	$S=2.493+KV*0.144-MS*0.069-HALT4*0.017$
ABT	0.93	0.84	$S=2.179+KV*0.167-HALT4*0.047+HM*0.287$
ABS	0.85	0.71	$S=1.547+KV*0.143-MS*0.087$

*S= calculated relative wear (1.0 corresponds to HABT16 porphyry from Älvdal)*

*KV= Nordic ball mill value*

*MS= Maximum aggregate size*

*OPTH= content of aggregate in the largest aggregate fraction (for HABS16 this is the quantity of 12-16 mm stones)*

*HALT4= content of aggregate > 4 mm*

*HM= Air void ratio in percentage by volume according to Marshall*

From the equations in the table, one can note that the air void ratio, HM according to the model, affects the magnitude of wear only in dense graded asphalt concrete, ABT.

In the ABS pavements, according to the model, it is the Nordic ball mill value and the largest aggregate size that most affect the magnitude of wear. The content of coarse aggregate is not included in the equation due to the fact that the variation in stone content is not very great between different ABS pavements.

In our continued work on the model, for reasons of simplicity the same equation was used for ABT and ABS pavements. Furthermore, the content of the > 4 mm

aggregate was used to describe the content of coarse aggregate in the composition of the wearing courses.

### ***Partial model for distribution of transverse wear***

The distribution of wear across the width of the traffic lane provides very important information in order to be able to use the model to calculate the service life of a pavement, since it is the magnitude of the rut depth that determines when maintenance has to be carried out. The distribution model is based on the lateral position of traffic (passenger vehicles) and is relatively close to the normal distribution, according to measurements done by VTI. Standard deviation of the distribution of transverse position normally varies between 0.20 to 0.45 m depending on the standard cross-section of the road. On roads with extra wide traffic lanes and roads with shoulders, the standard deviation of the transverse distribution is close to 0.45 m. On roads with narrow traffic lanes and on express ways and highways with several lanes in each direction, standard deviation is closer to 0.25 and down towards 0.20 on roads with an extremely high volume of traffic.

The distribution model is based on a reverse, somewhat modified normal distribution curve, developed through comparisons with wear profiles measured from a large number of roads and which has proved to be a good reflection of reality. The model was developed in Excel where the entire profile of the traffic lane was drawn up using input data such as the standard deviation of the distribution of transverse position. Input data that describes the magnitude of wear was gathered from the first partial model.

### **Computerised composite model**

The two partial models were brought together in a computer version for calculation of rut depth, service life, and annual cost. All the calculations were entirely based on wear trends from studded tires and thus do not take into account any rut formation that could have other causes. The computerised model version consists primarily of three blocks of input data and diagrams that show the calculated rut profile and the wear trend, respectively.

### ***Input data – pavement (mineral aggregate)***

The first block of input data consists of input data that describes the wear properties of the wearing course and in principle it looks like this:

<b>Chart heading:</b>	<b>Nynäsvägen</b>		
<b>Chart subheading:</b>	<b>Rut wear during 3 winters</b>		
<b>Stone content &gt; 4 mm (HALT4):</b>	<b>70</b>	<b>% by weight</b>	
<b>Largest stone size (MS):</b>	<b>16</b>	<b>mm</b>	
<b>Ball mill value (KV):</b>	<b>5.5</b>		

This portion shows the headings that should be used in the chart.

*Stone content > 4 mm (HALT4)* is the content of material larger than 4 mm in the wearing course in question. If the wearing course in the above example is ABS16, the coarse aggregate fractions, i.e. 4-8, 8-11 and 12-16 mm, constitute 70 % by weight of all stone material.

*Largest stone size (MS)* is the size of the nominally largest aggregate size, in this example 16 mm.

The *ball mill value (KV)* for the largest aggregate fraction (8-11 or 11-16 mm) is entered.

#### ***Input data - traffic and road***

In the other worksheet, traffic related input data that affects the magnitude of wear, is requested.

<b>Standard cross section (1/2/3/4/5/6):</b>	<b>5</b>	<b>(1=7 m; 2=9 m; 3=13 m; 4=wide lanes; 5=express way; 6=tunnel)</b>	
<b>Permitted speed:</b>	<b>90</b>	<b>(50, 70, 90 or 110 km/h)</b>	
<b>ADT traffic lane:</b>	<b>10000</b>	<b>vehicles/day</b>	
<b>Wear period/year:</b>	<b>180</b>	<b>winter days/year</b>	
<b>Studded tire share:</b>	<b>50</b>	<b>% (aver. during the wear period)</b>	
<b>Lightweight studded tire share:</b>	<b>50</b>	<b>% (0,10,20,30....%)</b>	
<b>Decide (salt) road (Y/N):</b>	<b>Y</b>		
<b>No. of calculation years:</b>	<b>3</b>		
<b>Permitted rut depth:</b>	<b>17</b>	<b>mm</b>	
<b>Estimated other rut depth:</b>	<b>4</b>	<b>mm</b>	
<b>Available rut depth wear:</b>	<b>13</b>	<b>mm</b>	

*ADT = Average annual daily traffic*

#### ***Standard cross-section***

The first thing described in this worksheet is the standard cross-section of the road in question. So far there are six different standard cross-sections to choose between. The model describes each cross-section through the standard deviation for the lateral position distribution of passenger vehicles.

The following standard deviations were used to describe the distribution of lateral position:

<b>Standard</b>	<b>Lane width, m</b>	<b>St. dev. mm</b>
1	7	275
2	9	350
3	13	450
4	Wide lanes	500
5	Motor road	250
6	Tunnel	225

The above data may have to be modified after validation of the model.

### ***Permitted speed***

Permitted speed is recorded as four speeds. The following relations were used:

<b>Speed, km/hour</b>	<b>Wear factor</b>
50	0.65
70	0.90
90	1.20
110	1.50

Above wear factors were gathered from field tests of pavement slabs that included two pavement types, five stone materials and three different speeds.

### ***Average annual daily traffic (ADT) in driving lanes***

ADT passenger vehicles for the traffic lanes included in the prediction are also shown.

### ***Wear period/year***

Wear period/year refers to the number of winter days per year. A winter day means a day when use of studded tires is more than 5 % (normally 180 days).

### ***Studded tire share***

Then the use of studded tires is shown in percent in the form of an average value during the recorded wear period. This information is *very significant* to the predicting ability of the model for reasons that are easy to understand. Therefore, it is important for the input data to be relevant. In order to obtain reliable data on the use of studded tires, frequent counting of studded tires during the entire winter period (November - April) is required. In southern Sweden, it is necessary to count studded tires at least twice per month since the use of studded tires can vary greatly from year to year and from month to month, depending on alternately mild and cold winters or periods of heavy or little snow during the winter season. Visual counting of studded tires should include around 200 vehicles and this can be done in a large parking lot, such as a mall or gas station. Acoustic methods (listening) do not work well because it is harder to hear tires with lightweight

studs than the older steel studs, particularly if conditions are snowy, icy or wet on the road.

### ***Share of tires with lightweight studs***

The number of tires with lightweight studs is recorded in percent. Since 1992, the percentage of less damaging studded tires has increased continuously as conventional studded tires are being replaced with tires with lightweight studs. According to tests in VTI's Road Simulator, tires with lightweight stud's (1.0 g) result in about half as much wear as tires with heavier steel studs (1.8 g). The annual recurring control measurements on the road have also confirmed this, and this means that wear has been reduced significantly, relatively speaking, in the most recent years (1992-97).

The following wear factors were used to describe the effect of a growing number of tires with lightweight studs. Correction is done only at 50 % of estimated share of lightweight studded tires, since the remaining tires with steel studs are getting old (at least 5-6 years) and worn and therefore less damaging to the pavement. This very likely means that the correction (for Swedish conditions) for this parameter soon can be eliminated from the model (validation will follow up on this).

<b>Share of light-weight studs, %</b>	<b>Wear factor</b>
0	1.40
10	1.25
20	1.10
30	0.95
40 <sup>1)</sup>	0.80
50	0.75
60	0.75
70	0.75
80	0.75
90	0.75
100	0.75

<sup>1)</sup> Value used at validation in 1996-97

### ***Salted (deiced) road***

Crucial to the extent of wear is also whether the road is de-iced or not during the winter season. This question is answered by Yes or No. Data describing the difference in wear between a salted and unsalted road was not available, so that the model for the time being employs the correction factor given in ROAD 94 (the general technical specification of the Swedish National Road Administration). A salted road means a wetter road surface compared to an unsalted road surface and these increases wear. Unsalted road surfaces may also be ice covered and this reduces wear on the road. These parameters should be investigated more closely when the model is modified (if the model is to be better adapted to northern Sweden).

***Number of calculation years***

Also noted are how many years or winter seasons that the calculation or prediction of the wear profile should include.

***Permitted rut depth***

Permitted rut depth is the rut depth noted in ROAD 94 for the greatest permitted rut depth for the type of road in question.

***Estimated other rut depth***

Estimated other rut depth is the rut depth that is not related to wear produced by studded tires, for example post compacting and deformation. R&D work is going on in order to produce a prediction model for deformation in asphalt-bonded pavements, and at a later stage this can be connected to the wear model for studded tire traffic.

***Available rut depth wears***

Available rut depth wear is the difference between permitted rut depths and estimated other rut depth.

***Input data - costs***

The third input data worksheet constitutes the basis for the financial evaluation of the surfacing measure, but still only from the point of view of wear from studded tires:

<b>Mineral aggregate</b>	<b>Weight %</b>	<b>Price SEK/tonne</b>	<b>Density g/cm<sup>3</sup></b>	<b>Price SEK</b>
Filler:	<b>7</b>	<b>100</b>	2.66	7.00
Size 0-2 mm:	<b>13</b>	<b>55</b>	2.70	7.15
Size 2-4 mm:	<b>10</b>	<b>60</b>	2.70	6.00
Size 4-8 mm:	<b>10</b>	<b>150</b>	2.66	15.00
Size 8-12 mm:	<b>20</b>	<b>280</b>	2.66	56.00
Size 12-16 mm:	<b>40</b>	<b>280</b>	2.66	112.00
Size 16-20 mm:	-	-	-	-
Total % of aggregate:	100		2.67	203.15
Binder content:	6.0	1700	1.00	102,00
Total:			2.426	

<b>Total costs:</b>				
Aggregate:	<b>203</b>	SEK/t asphalt mix		
Bitumen:	<b>102</b>	"		
Additives:	-	"		
Production in asphalt plant:	<b>25</b>	"		
Set-up cost:	<b>0,05</b>	"		
Transportation (asphalt plant to road site):	<b>150</b>	"		
Paving:	<b>30</b>	"		
Other:	<b>0</b>	"		
Asphalt layer thickness:	<b>37</b>	mm		
<b>Total kg/m<sup>2</sup></b>	<b>90</b>	kg/ m <sup>2</sup>		
<b>Total SEK/tonne:</b>	<b>510.00</b>	SEK/t		
<b>Total SEK/ m<sup>2</sup>:</b>	<b>45.80</b>	SEK/ m <sup>2</sup>		
<b>Annual cost:</b>	<b>5.09</b>	SEK/ m <sup>2</sup>		

By entering the aggregate composition and by recording the share in percent and price in SEK per tonne delivered to the asphalt works for each fraction, total aggregate cost is calculated.

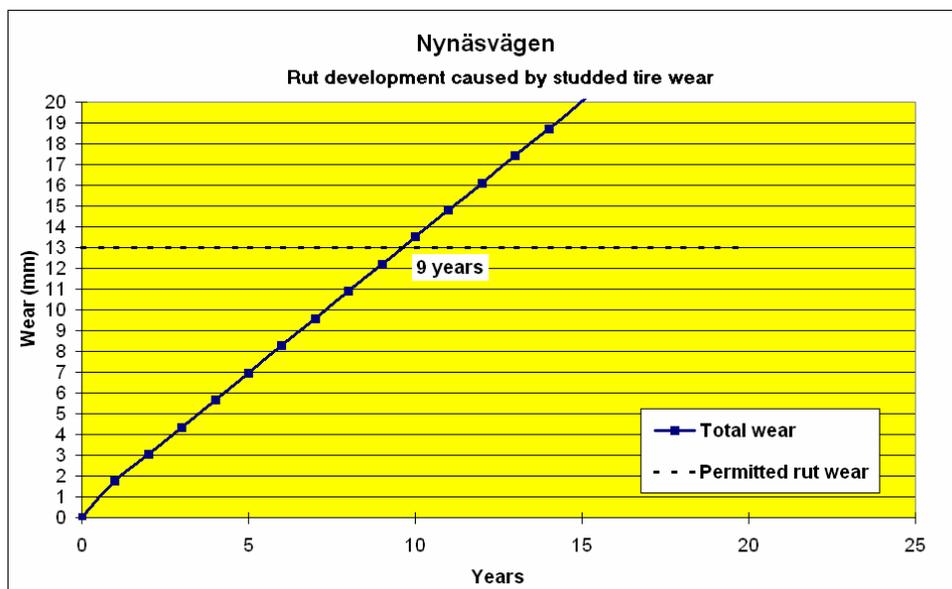
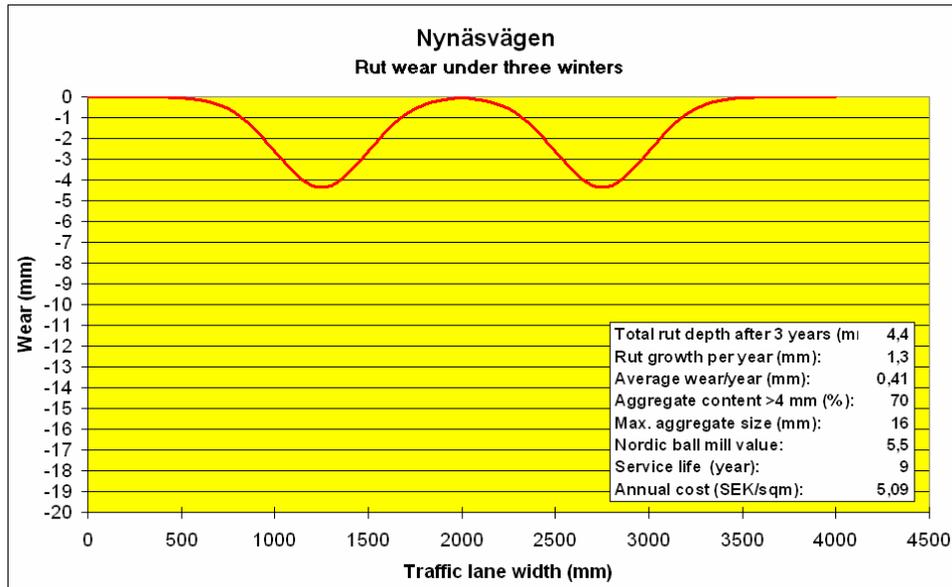
To this is added the cost of bitumen, any additives, production cost at the asphalt mixing plant, set-up cost, transportation cost, laying cost and any other costs together with the amount of paving in kg/m<sup>2</sup>. With the aid of these data, we obtain the total production cost in Swedish kronor per square meter. If the price of rolled bitumen per m<sup>2</sup> is known, it can also be entered directly.

The production cost is then divided by the service life calculated by the prediction model and an annual cost in Swedish kronor per square meters is obtained. Even if the service life solely from the point of view of wear may be more than 20 years, the limit for service life has been set at 20 years in the model since by that time it is likely that some measure will be required for reasons other than wear. At present, the annual cost calculation does not take interest into account. However, it is quite possible to add it.

### ***Output data - abrasive wear profile, service life and annual cost***

The calculated wear profile across the number of included calculation years is presented in graphic format:

Apart from the *cross-section profile*, the first diagram shows *total rut depth* after the selected calculation period, *rut growth* per year, and calculated *service life* and *annual cost* in Swedish kronor per square meter.



The second diagram shows the *development of ruts* created by *traffic with studded tires* on the road. *Initial wear* was taken into consideration in that abrasive wear is calculated with a 100 % increase for the first 300,000 passing vehicles with studded tires. Relatively speaking, asphalt pavement is always worn down more when it is new than when the bituminous mortar has had time to wear off and the stones have lost their edges.

### Validation of the model

During the winter of 1996-97, the model was validated against 16 different wearing courses (ABS and ABT). All data that constitute input data in the model were gathered and wear measurements were taken on 1-6 year old pavements with varying types of surfacing, road categories and speed limits. The properties of the selected pavements also vary with regard to aggregate quality, largest aggregate size and Nordic ball mill value. The pavements are located in the provinces of Halland, Bohuslän, Västergötland, Östergötland and Södermanland.

For each control object, the data gathered with respect to wearing course, traffic and road have been entered into the model. After this the wear factor and standard deviation for the lateral position distribution (STD dev) were corrected so that the average and maximum rut depth coincided with the values taken from the road. The results of the validation are shown in the table below.

### *Results of validation*

Road	Road section No.	Average wear mm	Rut wear Mm	Wear factor mm	Lateral distr. Std dev	Number of days
<b>E6, Åbro-Kallebäck</b>	1	0.6	1.5	0.00103	350	172
	3	0.7	1.5	0.00108	360	172
	5	0.71	1.7	0.00108	340	172
	7	0.59	1.5	0.00089	325	172
	8	0.55	1.4	0.00095	320	172
	10	0.64	1.4	0.00135	355	172
<b>Länna road 73</b>	1	0.54	1.1	0.00134	380	140
	2	0.38	0.7	0.00110	410	140
	3	0.3	0.6	0.00087	410	140
<b>Borg E4</b>	1	0.27	0.6	0.00080	390	170
	2	0.27	0.5	0.00080	400	170
<b>Alingsås E20</b>	1	0.42	0.7	(0.00190 <sup>1)</sup> )	445	136
<b>Ytterby road 168</b>	1	0.24	0.4	0.00120	445	138
<b>Huvden road 190</b>	1	0.17	0.4	(0.00220 <sup>1)</sup> )	390	138
<b>Forsbäck road 940</b>	1	0.15	0.4	0.00080	335	138
<b>Kungälv E6</b>	1	0.29	0.7	(0.00054 <sup>2)</sup> )	335	135
			<b>Mean value:</b>	0.00102		
			<b>Std dev.:</b>	0,00019		

<sup>1)</sup> The high value is due to the fact that the road surface had not yet gone through its initial wear stage (initial wear).

<sup>2)</sup> The low value could be due to the fact that the control section is located on a down hill stretch of the road.

Developments in recent years in the field of studded tires cause a problem when it comes to validating the model. New types of studs and studded tires have gradually been developed and these have proved to be much less damaging to road surfaces than older types of studded tires. This means that the number of vehicles with increasingly less damaging studded tires has increased and probably will increase further during the next few years, as this has occurred gradually during the 1990's. One example is the gradual reduction in stud weight, reductions in stud protrusion and stud force, as well as a reduction in the number of studs per tire. However, within a couple of years the majority of tires with steel studs of the older and heavier type (1.8 g) should be gone from the vehicle supply, since sales of such tires ceased at the beginning of the 90's. It could take several years until entirely stable wear conditions will exist on our roads, however.

Copies of the first version of the wear model have been distributed to a number of clients within the National Road Administration for evaluation of the model and the program from a user's point of view.

## **Background data**

Mapping and quantification of the parameters that effect the ability of pavements (asphalt material) to resist wear from studs derive from a large number of trial slabs tested in the Road Simulator or on roads, as well as from full scale test roads. This primarily involves parameters related to materials engineering, but it also has been possible to study design quality, traffic and climate effects through these tests. The following factors were studied and their significance with regard to wear from studs is shown within parentheses:

### ***Materials engineering factors***

- Aggregate quality (very great)
- Coarse aggregate content (very great)
- Largest aggregate size (sometimes great)
- Type of wearing course (very great)
- Binder type (less)

### ***Production dependent factors***

- Crushing procedure - cubical particle shape (sometimes great)
- Degree of compaction - air void ratio (sometimes great)

### ***External factors***

- Vehicle speed (great)
- Type of studs, stud force (great)
- Climate (less)

Apart from these factors, the magnitude of the wear from studded tires is affected by the amount of traffic, the percentage of vehicles with studded tires, the lateral position of traffic, wet and/or dry or snow and/or ice covered road surface. All background material is available in a large number of reports, bulletins, and reprints from recent years (see bibliography). *Notat 21-1997* contains a detailed description of the background data for the wear model and the equipment and methods used to measure the wear resistance of asphalt pavements. The current report shows only the types of pavement and mineral aggregate that were included in these studies.

### ***Type of wearing courses and mineral aggregate***

It is important to remember that the data for the model were gathered from a number of different studies (commissioned research) with a variety of objectives and requests, so that the number of wearing courses and mineral aggregates do not fully cover all variables. For example, the number of wearing courses with the largest aggregate sizes of 8 and 20 mm are limited. With respect to speciality stone, such as porphyry or quartzite, these are included among the coarser stone material fractions, > 4 (most common), or > 8 mm. The content of fine fractions and filler consists of local material. Normally, cellulose fibre is also found in stone mastic asphalt, but in some cases it is mineral fibre. It is also important to point out that the wear model does not include porous asphalt. On that type of wearing course, the ageing and durability properties of the material are of crucial importance to wear resistance in a long-term perspective and these parameters are not captured in this model.



# Winter Tyres – Traffic Safety

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## **BACKGROUND**

During the winter 1993/94, the Swedish National Road Administration received considerable criticism for its winter maintenance and in particular for the high consumption of road salt. This led to discussions on changing the rules for winter maintenance. Some ice or snow was temporarily allowed on the roads with high winter maintenance standard. More roads were degraded to lower winter maintenance standard where ice or snow were permanently permitted. In addition, certain changes intended to influence driver behaviour and vehicle equipment for example mandating the use of winter tyres were to be studied.

The purpose of the first investigation described in this paper was to calculate the socio-economic consequences that may be expected from a requirement on winter tyres in various circumstances. The different proposals were a requirement of winter tyres

- during the whole winter,
- only during midwinter or
- only on slippery roads.

Winter tyres can be with or without studs. As earlier socio-economic studies of tyres were analysing a ban of studded tyres this was included to compare results when using different models.

In the second investigation in this paper the traffic safety effect of the requirement is studied. A requirement of using winter tyres when it is slippery was selected based on facts from the first investigation.

The calculations in the first investigation were made for winter 1993/1994 and for winter 1999/2000. The conditions in winter 1993/1994, a fairly normal winter meteorologically, form the basis for the calculations. The conditions in 1999/2000 were the same except for the assumptions that all those using studded tyres in 1993/1994 were supposed to use lightweight studs in 1999/2000 and that wear resistant pavements will be more common. All other factors, such as winter maintenance, were assumed to be the same as in 1993/1994. About 64 % of the passenger cars used studded tyres in December 1993 and their vehicle mileage on ice or snow was 76 % of the total. Summer tyres were used by 23 % of the passenger cars while their vehicle mileage on ice or snow was 9 % of the total. The rest stands for other winter tyres without studs.

The following effects are included in the first investigation:

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- Accidents (direct: at slipperiness; indirect: because of pavement wear)
- Road wear (pavement and road markings, cleaning traffic signs)
- Car costs (tyres/rims, fuel consumption, washing)
- Environment (only washing of cars)

The effects on road safety that are assumed are a 40 % decrease in accidents in icy/snowy road conditions on rural roads when using studded tyres and a 35 % decrease in accidents in built-up areas compared with summer tyres. The corresponding figures for other winter tyres are 25 % and 20 %. Each type includes both good and bad tyres such as in use at the beginning of 1990. (Öberg et al, 1993, and Jung- hard, 1992)

### ***A BAN OF STUDDED TYRES (Carlsson et al, 1995)***

If a ban of studded tyres is introduced the redistribution of vehicle activity is calculated to lead to 80 % of the earlier traffic with studded tyres acquiring stud winter tyres without studs and 20 % driving on summer tyres.

From 1 November 1993 to 15 April 1994 the police reported 38,248 accidents and out of that passenger cars were involved in 33,735 (in icy or snowy conditions there were 16,271 passenger car accidents). The model (safety effect of different tyres) used gave that the ban of studded tyres would result in an accident increase of about 3,000 – 3,600 accidents/winter. There are also indirect accident effects, caused by the use of studded tyres, such as higher friction on ice or snow and higher wet friction on pavements, since the studs create a coarse surface texture and this will with a ban of studded tyres further increase the number of accidents. Studs produce ruts and poorer visibility which will decrease the number of accidents with a ban. The sum of these indirect effects is an accident increase of 600 - 700 accidents because of not using studded tyres.

The total estimated number of fatalities in road accidents has increased by somewhat just fewer than 20, seriously injured with hardly 170 and slightly injured with hardly 700 persons. These values are uncertain and need more research.

When measuring road wear from traffic with studded tyres, the SPS index is normally used. SPS is the Swedish abbreviation for specific wear and indicates the number of tonnes of abraded asphalt per kilometre of road and million vehicles with studded tyres, or the number of grams of abraded asphalt per kilometre of road and vehicle with studded tyres. The average SPS index has been calculated after measurements on roads with various AADT. With steel studs, the SPS index varied between 22 and 35 g/km for the various classes of traffic, with an average of 26g/km. The SPS index for lightweight studs is half of these figures.

During winter 1993/94, it is estimated that 17 % of the vehicles with studded tyres had lightweight studs. This gives a weighted SPS index of 24 g/km, which implies total road pavement wear of 300,000 tonnes, valued at approximately SEK 150 million. To compensate for winters with more troublesome wear levels, the cost of wear can be said to be in the range of SEK 150-200 million. Wear on road markings and washing dirt spray from road traffic signs is estimated to cost SEK 35-70 million/year. On state-owned roads this wear of pavement and road markings correspond to a cost of about SEK 2,500 – 3,600 per km and year.

In the winter 1999/2000 the average SPS index was calculated to be 11 g/km, giving a total road wear of about 130,000 tonnes worth SEK 65-90 million at 1995 prices corresponding to SEK 900 – 1,200 per km and year. Wear on road markings and dirt spray on road traffic signs is put at SEK 20-35 million/year or SEK 270 – 470 per km and year.

The costs for motorists using studded tyres would have decreased if studded tyres would have been banned. The motorist pays for winter tyres and extra rims, and also the cost of wheel changing. The annual saving will be about SEK 110 million.

Fuel consumption is calculated to decrease by SEK 5 million owing to an assumed difference of 2 % between summer tyres and winter tyres. It is also assumed that no difference in fuel consumption exists between studded and studless winter tyres.

The use of studded tyres, means that vehicles need to be cleaned more often since road wear increases. In this study the studs necessitate 2-4 extra washes during a winter. If studded tyres would have been banned this would give a cost decrease to car owners of SEK 200-600 million in 1993/94. Owing to the road wear in 1999/2000, the savings will be only SEK 130-300 million.

The only environmental effect included is the effect of car washing. Vehicle washing requires stronger agents than would be necessary if tyre studs were not used. Emissions of petroleum-based solvents, attributable to studded tyres would then amount to 1,500-3,000 tonnes for 1993/94. Based on the Swedish National Road Administration's environmental evaluation, this would lead to an environmental cost of SEK 25-50 million/year. In 1999/2000, the environmental cost of vehicle washing necessitated by the use of studded tyres will have fallen to SEK 10-20 million.

No health effects due to pavement wear/air pollution are included.

The estimated cost effects of banning studded tyres in Sweden are summarized in table 1. The effect of winter/studded tyres on accidents is considerable and the cost of the increase in accidents because of a ban of studded tyres is not offset by other cost decreases. The effect on the environment is, however, difficult to measure and evaluate, and therefore only vehicle washes are included in table 1. With the above results for the other effects, this means that the total environmental effect may become fairly large before equilibrium is reached. Health effects were not at all included.

Table 1. The cost change for a ban of studded tyres (SEK million/year).

	Increase	Decrease	
		1993/1994	1999/2000
Accidents direct indirect	1,190–1,450 240–290		
Road Wear pavement road markings sign		150–200 35–70	65–90 20–35
Car costs tyres/rims fuel consumption washing		110 5 300–700	110 5 130–300
Environment car washing the rest, air pollution, noise etc.		25–50 ?	10–20 ?
Health		?	?
Total	1,430-1,740	625–1,135 +?	340-560 +?

### ***PREDICTIONS OF A REQUIREMENT OF WINTER TYRES (Carlsson and Öberg, 1995)***

In the case of a requirement on winter tyres in slippery conditions it is possible that

- passenger car mileage with summer tyres on ice or snow will be eliminated, i.e. not post boned until bare road conditions has been restored
- passenger car mileage with summer tyres in icy or snowy conditions will be post boned until bare road conditions prevail
- all motorists will change to winter tyres during the restricted season.

In the calculations the requirement of using winter tyres are compared with the use in the winter 1993/1994. The distribution of vehicle mileage among different tyres controls the change in benefit/cost implied by the various alternatives, based on conditions in winter 1993/1994. The distribution used here is that the ones using summer tyres in the winter before a requirement will after a requirement

- 15 percentage unit use studded tyres,
- 5 percentage unit use winter tyres without studs
- 3 percentage unit will not drive when it is slippery on the road.

The road safety benefit with this requirement is greater than the known negative effects of the requirement. In sudden slipperiness, it is possible that some vehicle mileage with summer tyres will take place, which will decrease the highest traffic safety value above. The number of car accidents reported by the police will decrease by 1,100–1,400. In these cars will 6 – 7 people less be killed, 50 – 60 less

seriously injured and 200 – 250 less slightly injured when the requirement lasts from November 1 to April 15. The calculation is summarized in table 2.

Table 2 Requirement on winter tyres in slippery road conditions compared to the use of tyres in the winter 1993/1994 in Sweden (SEK million/year).

	Decrease	Increase	
		1993/1994	1999/2000
Accidents direct indirect	385–485 75–95		
Road Wear pavement road markings sign		25–35 10	10–15 5
Car costs tyres/rims fuel consumption washing		200 30 50–120	200 30 20–50
Environment car washing the rest		5–10 ?	0–5 ?
Health		?	?
Total	460–580	320–405 +?	265–305 +?

### **TRAFFIC SAFETY EFFECT OF THE WINTER TYRE LAW (Öberg et al, 2001)**

In the summer 1999 the government regulated the use of winter tyres. Since the winter 1999/2000 Sweden therefore has a requirement on passenger cars and other vehicles with a total weight of less than 3.5 tonnes of using winter tyres (studded or unstudded) when travelling in slippery road conditions during the period December 1 – March 31.

If it is not slippery conditions it is allowed to use summer tyres in the winter. That means that if you must not use your car everyday whatever the condition is you don't have to change tyres.

After two winters with the requirement VTI studied the use of winter tyres and traffic safety effect. The information in the accident data base has been changed between the two studies in this paper in the way that only accidents with injured or killed people are stored after year 2000.

In the most southern part of Sweden the use of summer tyres in the winter is almost 10 %. In and around the biggest cities some percent use summer tyres but elsewhere almost no one uses summer tyres after the requirement.

In the accident analyses, the two winters with the regulation in effect are compared with the two winters just before. Already before the regulation almost every car in the northern half of Sweden used winter tyres, mainly studded tyres. The regulation will not change the use of tyres there. This region is therefore used

as a control area and in the south the neighbour country Denmark was used as a control area. They had not changed their rules.

Accidents with seriously injured and fatalities in icy/snowy road conditions decreased with 11 or 14 % depending on the assumption if winter tyres also have a traffic safety effect on bare roads or not, see tables 3 and 4. The decrease is not statistically significant.

Table 3 Effect on number of accidents with killed or seriously injured road-user of the winter tyre law when it is assumed that winter tyre use do not affect the accident probability on roads with bar condition.

Relative change	95%-confidence interval	
	Lower	Upper
- 11 %	- 33 %	+ 19 %

Table 4 Effect on number of accidents with killed or seriously injured road-user of the winter tyre law when it is assumed that winter tyre use do affect the accident probability even on roads with bar condition.

Relative change	95%-confidence interval	
	Lower	Upper
- 14 %	- 33 %	+ 9 %

Using the effects determined in this study it was possible to estimate the change in killed and seriously injured road-users and compare them with the prognosis made back in 1995. It turned out that the prognosis made in 1995 about the traffic safety effect had almost the same result as the recently analysed accidents data, se table 5.

Table 5 Prediction and effect of the winter tyre law on persons severely injured and killed in traffic accidents.

Effect of regulation on in accidents	Prediction calculated 1995	Effect calculated 2001
Seriously injured	42 – 52 less	49 – 63 less
Killed	5 – 6 less	7 – 9 less

A research project has started 2003 in Sweden about particles from stud wear of pavements. The amount in the air and the health impact of that will be studied.

## **ACKNOWLEDGEMENT**

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## **REFERENCES**

- Carlsson, Arne; Centrell, Per & Öberg, Gudrun. **Studded tyres. Socio-economic calculations.** Swedish National Road and Transport Research Institute. Meddelande 756A, 1995. In English.
- Carlsson, Arne och Öberg, Gudrun. **Winter tyres. Effects of proposed rules.** Swedish National Road and Transport Research Institute. Meddelande 757A, 1995. In English.
- Junghard O: **Estimating the traffic safety effect of studded tires.** Accident Analysis and Prevention Vol 24 pp 357-61. 1992.
- Öberg, Gudrun; Junghard, Ola & Wiklund, Mats. **A Study of Methods of calculating the connection between the use of studded tyres and road safety.** Swedish National Road and Transport Research Institute VTI meddelande 722, 1993. In Swedish with Summary in English.
- Öberg, Gudrun; Velin, Hans & Wiklund, Mats. **Effect of Winter Tyre Law.** Swedish National Road and Transport Research Institute VTI Rapport 479, 2001. In Swedish with Summary in English.

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