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Calibration of the Swedish studded tyre abrasion wear prediction model with implication for the NORTRIP road dust emission model

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ABSTRACT

An experimentally based prediction model of road abrasion wear due to studded tyres is available in Sweden and has been found to work well. However, it has not been validated since 2007, and since then road surfaces and tyre design have developed, and the question has arisen regarding the model's current validity. The abrasion wear model is used in the NORTRIP emission model (NOn-exhaust Road Traffic Induced Particle emission modelling), and the effect of a recalibrated abrasion wear model on the emission model is shown. In this paper, the abrasion wear model is compared to full-scale field measurements at several recently constructed roads in Sweden to investigate its validity, while also proposing changes to allow for continued use. It is concluded that the model overestimates the wear and an update is suggested. In addition, the impact on NORTRIP emission predictions is briefly investigated. There were also indications that NORTRIP is affected by the abrasion model overestimating the contribution of pavement wear to the particle emissions.

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KEYWORDS
PM10; Studded tyre; Abrasion wear; Model; Road dust; Pavement

Introduction

In cold regions, pavement surface rutting is due to permanent deformation in the different layers of the structure as well as surface wear due to the use of studded tyres. The permanent deformation in the unbound layers mainly takes place during the spring thaw and rainy periods (Cerni *et al.* 2012, Rahman and Erlingsson 2015, Erlingsson *et al.* 2017), whilst the bituminous layers exhibit plastic deformations mainly when the asphalt layers are warm, i.e. during the summer period (Lytton *et al.* 1993, Di Benedetto *et al.* 2013, Ahmed and Erlingsson 2015). Studded tyre abrasion wear, on the other hand, takes place during the winter months, also forming particle pollution. Studded tyres are allowed (unrestricted or restricted use) in several countries, e.g. Finland, Norway, Canada, Russia and many of the states in the U.S.A. (Zubeck *et al.* 2004). In Sweden, light traffic usage of studded tyres began in the 1960s (Zubeck *et al.* 2004, Gustafsson *et al.* 2006, Doré and Zubeck 2009), with the main purpose to improve vehicle manoeuvring and thus improve traffic safety during winter traffic conditions. The main drawbacks of studded tyres are linked to the surface abrasion caused by the studs repeatedly hitting the pavement surface. Further, negative environmental aspects include aerosol pollution in the form of non-exhaust PM_{10} (particulate matter with an aerodynamic diameter smaller than 10 µm, e.g. Thorpe and Harrison 2008) as well as noise pollution (Laurinavičius *et al.* 2010).

In urban environments, a large part of the measured mass concentration of airborne particles (PM_{10}) consists of non-exhaust particles (wear particles from the road, tyre and brake sources) in areas where studded tyres are used (WHO 2005, Gustafsson *et al.* 2011). PM_{10} is linked to several different health issues, including increased cardiovascular and cerebrovascular mortality (e.g. Stafoggia *et al.* 2013) but also respiratory diseases and daily mortality (e.g. Brunekreef and Forsberg 2005, Forsberg *et al.* 2005, Meister *et al.* 2012). In another study by Denier van der Gon *et al.* (2012), a consensus statement was given stating that health risks due to non-exhaust PM_{10} from wear emissions are non-negligible. Furthermore, Amato *et al.* (2014) have concluded in another review that the non-exhaust PM_{10} may be as hazardous as exhaust PM_{10}, although dependant on which property investigated, since both size, mass and surface chemistry of the particle will impact on the toxicity.

In recent years abrasion by studded tyres has decreased due to legislation aiming at reducing road wear and wear particle emissions; limiting the number of studs per tyre, improvement in stud types and their weight, and allowing only seasonal use of studs. Another aspect which has led to a decrease in abrasion wear is the technological development of surface courses, including more stringent aggregate requirements, resulting in more abrasion resistant wear surfacings'. Currently, during the winter period, the studded tyre usage for light traffic is estimated to be 45–96% in Sweden, depending on geographic region (Swedish Transport Administration 2016a). In Norway, studded tyre usage ranges between 12% and 79% (weighted by traffic volume in the region) (Norwegian Public Roads Administration 2015) and in Finland, the share is 76–99% depending on region (Unhola 2016). Over the last few decades, several regulations have been introduced in Sweden as an incitement

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to push the development of studded tyres to decrease abrasion wear. As reported by Jacobson and Wågberg (1997), the old type of steel studs was banned for new tyres in 1992, drastically reducing stud weight. Thus, around 1997 most studded tyres had lightweight studs. Since then, the number of studs and the weight of studs, etc., are regulated in Sweden (TSFS, 2009:19, 2009:90) as well as in Finland and Norway. One example on how the stud weight has a large impact on the abrasion wear, resulting in the discussed legislation, is given in Figure 1. The data is based on Gustafson (1992) from a full-scale Road Simulator (RS, described later) study. Note specifically that the abrasion is presented as the area worn, and that the plastic studs had a body of plastic and a pin of metal.

Larger roads and streets are publicly owned in most countries and thus financed and maintained by taxes. Prediction models of their degradation are required to optimise maintenance to allow efficient use of public funds. The pavement abrasion wear model studied here (at first with the Mineral aggregate sub-model) was developed and implemented in Sweden in 1997 (Jacobson and Wågberg 1997) with validations in 2000, 2005 and 2007 (Jacobson and Hornwall 2000, Jacobson 2005, Jacobson and Wågberg 2007) due to stud related changes and new wearing course types. In 2007 an alternative sub-model (the Prall sub-model) was introduced, with the main difference being the pavement indata required.

The Mineral aggregate sub-model is currently also used in the NORTRIP (NOn-exhaust Road Traffic Induced Particle) emission model for Nordic conditions, developed by the Nordic countries (Denby *et al.* 2013a). Previous emission models dealt with non-exhaust emissions in form of averaged emission factors, not taking weather effects into account, and thus excluding the build-up of a road dust loading, which is later available for suspension. NORTRIP was developed using a coupled road dust and surface moisture model to account for meteorological and traffic effects on road dust build up for prediction of non-exhaust emissions and calculation of emission factors (Denby *et al.* 2013b). NORTRIP is also used to model the impact of abatement strategies against non-exhaust PM_{10} emissions from traffic.

Due to lack of up-to-date validations of the wear model since the last update in 2007, built on abrasion wear data from the winter season of 2004/2005 for pavements constructed in 2004 or earlier, questions regarding current validity have been raised for the model, given the developments in regulations, road surfaces, studded tyre types (studs, material, etc.) and traffic.

Study objectives

The main purpose of this study was to determine the validity of the Swedish abrasion wear model for studded tyres, and to calibrate the model based on measurements performed during the last 14 years. A secondary objective was to investigate how the NORTRIP road dust emission model is affected in case of a recalibration of the abrasion model.

Abrasion wear model description

The Swedish abrasion wear prediction model was developed based on a full-scale experimental indoor circular road simulator (RS, also described in e.g. Gustafsson *et al.* 2008) and was further tested and later also validated with field performance data. The first version of the model was released in 1997 (Jacobson and Wågberg 1997, 2007). The intention was to predict mean and max profile wear due to abrasion caused by studded tyre usage for bituminous bounded surface courses.

The abrasion wear model consists of three parts:

(1) Calculation of the magnitude of the studded tyre abrasion per vehicle with studded tyres, based on one of the following sub-models:
  (a) the Mineral aggregate sub-model.
  (b) the Prall sub-model, added in 2007.
(2) Calculation of the abrasions distribution over one driving lane.
(3) Calculation of the yearly maintenance cost and lifespan of surface wear courses (not further discussed in this paper).

Required model input data

The abrasion wear prediction model requires both traffic and pavement data to operate. The traffic data consists of the annual

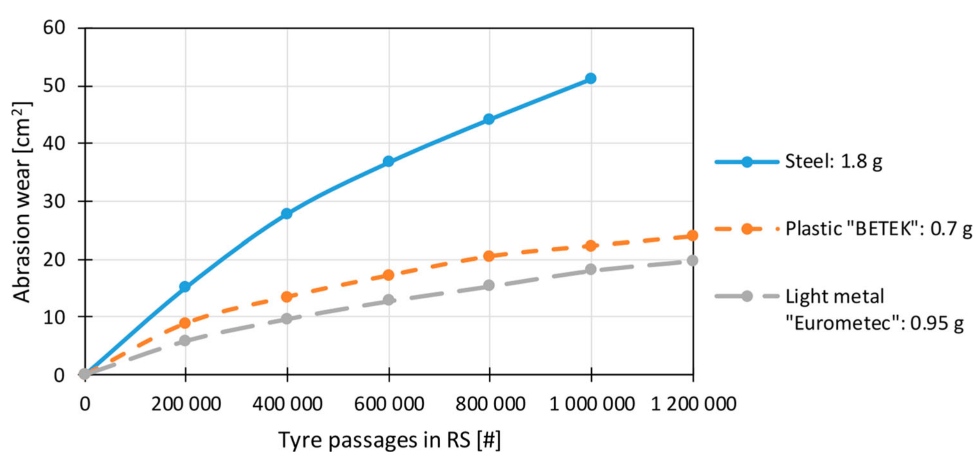


Figure 1. Impact of stud weight on pavement abrasion wear performed in the full-scale road simulator (RS), on Dense Asphalt Concrete with nominal maximum aggregate size 16 mm (DAC 16) pavement with porphyry aggregates. Data from Gustafson (1992).

average daily traffic in the investigated lane ($AADT_L$), limited to light traffic, and the share of studded tyres as well as the length of the wear period, defined as a number of days where the studded tyre share exceeds 5%. Further inputs are the allowed vehicle speed, road type and whether de-icing operations are used. The pavement data required consist of the largest aggregate size of the surface course, the Nordic abrasion value (CEN 2014) and the amount of aggregates with diameter larger than 4 mm when using the Mineral aggregate sub-model. To use the Prall sub-model, only the Prall abrasion value (CEN 2016) is required regarding pavement data.

The abrasion wear model

The Mineral aggregate sub-model was developed after extensive trials with laboratory manufactured slabs of two types of surface courses, Dense Asphalt Concrete (DAC) and Stone Mastic Asphalt (SMA), with the largest stone size varying between 12–20 mm and 8–20 mm, respectively. The pavements also had other variations in composition, e.g. mineral aggregate qualities and bituminous binder types (Jacobson and Wågberg 1997). Slabs were tested in an indoor circular RS facility (Figure 2). The tests were further complemented with field testing where slabs were positioned in different road test sections and exposed to real traffic and meteorological conditions.

The RS is located in an indoor climate chamber and has four operational axles, on which tyres are mounted. The RS requires 28 slabs (average slab size of 0.61 × 0.48 m) to form a full pavement ring (in average 5.25 m in diameter, 16.5 m in circumference), making it possible to test 14 different surfacings simultaneously (2 slabs per surfacing). The RS also allows for use of an eccentric movement for operational speeds of 30 km/h and higher, during which the tyres have a small lateral wander over parts of the pavement, in total 60 mm for all tyres at the time of construction (Kullberg 1944). A full period of this wander (back and forth) takes about five minutes, which corresponds to about 250 laps at the speed of 50 km/h. Typically, the axle load is set to 450 kg, and the tyre pressure is set to 2.5 bar (250 kPa).

During model development, the tests were performed at 85 km/h with a wet surface and a temperature in the chamber of around 0°C. Some variations in the test were also performed, e.g. tests at different speeds; with dry road surface. For all tests, the abrasion was measured with a laser profilometer at regular intervals in the range of 0–1.2 million tyre passages.

The field testing was performed by following up the abrasion wear on the different test sections with the same laser profilometer as previously mentioned, with measurements during spring and autumn to differentiate the abrasion wear caused by studded tyre abrasion from plastic deformation caused by the heavy traffic. A typical field result is presented in Figure 3.

A good correlation between abrasion wear of slabs in the RS and slabs exposed during 1–3 years to real field conditions was found during the model development ($R^2 = 0.82–0.97$) (Jacobson and Wågberg 2007). Two examples of the relation between the RS and field measurements are presented in Figure 4.

All measured abrasion wear data was put in relation to a reference pavement, i.e. DAC 16 /B85 (bitumen with penetration 70/100) with a specific hard porphyry aggregate from Älvdalen, Sweden, which was given the reference relative wear of 1.0. By performing a multiple linear regression analysis for all observed data, a regression model was determined (Jacobson and Wågberg 1997).

Relative wear

The relative abrasion wear of surface courses, RW [–] is calculated as:

$$RW = 2.493 + 0.144 \cdot A_N - 0.069 \cdot D_{max} - 0.017 \cdot MAS_4 \quad (1)$$

where A_N is the Nordic abrasion value [–] determined by CEN (2014), D_{max} is the largest aggregate size [mm] and MAS_4 is the mineral aggregate share with diameter > 4 mm [w.%]. The regression model is valid for A_N between 3 and 13, D_{max} in the range of 8–20 mm and MAS_4 between 40 w.% and 75 w.%. An example of how five different mineral types with different A_N relates to the measured abrasion wear in the field is given in Figure 5 (Jacobson and Wågberg 2007).

Using Equation (1) and the data used to produce the equation (Jacobson and Wågberg 2007), an R^2 of 0.81 is achieved (Figure 6).

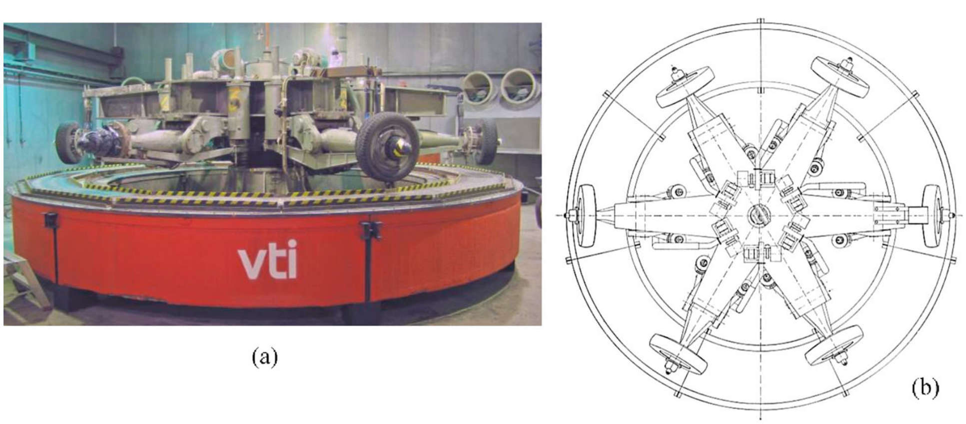


Figure 2. (a) The VTI Road Simulator (RS, photo: Mats Gustafsson, VTI). (b) Schematic top view of the RS (from Kullberg 1944). Only four axles are in use, due to irreparable damage, and the pavement slabs are laid in the wheel track. Notice that all axles have slightly different tracks.

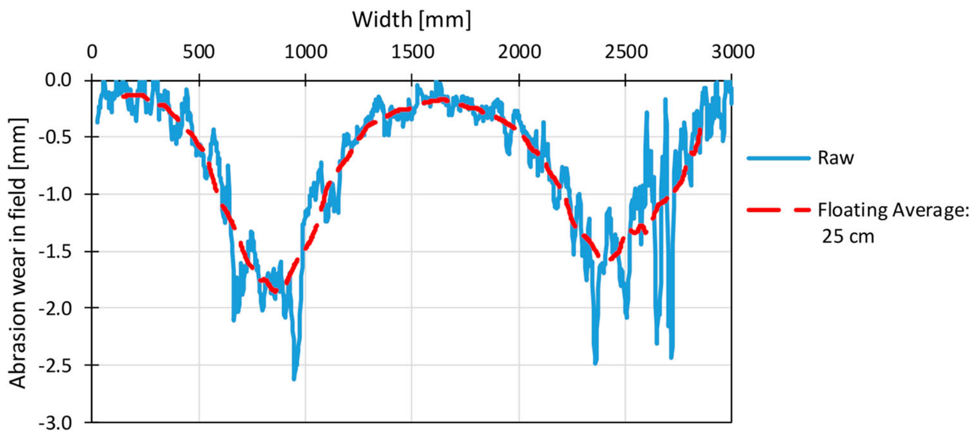


Figure 3. An example of field measured data, in this case the first line of five from the motorway E6 Mölndal 1 for the winter season of 2012–2013. Similar analyses are produced for measurements in the RS, with one wheel track only.

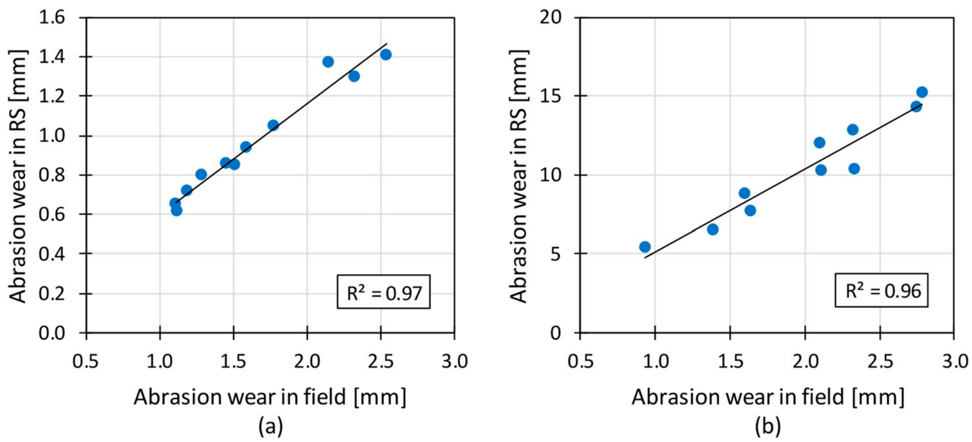


Figure 4. Two examples of the correlation between the abrasion wear of pavement slabs in the Road Simulator (RS) and pavement slabs in field. (a) Is redrawn from Jacobson and Wågberg (2007) and consists of SMA 8-20 and DAC 16 slabs. (b) Is redrawn from Gustafson (1992) and consist of DAC 12 and DAC 16 slabs. It should be observed that displayed abrasion wear in RS has a different amount of tyre passages than those displayed in field, and for a direct comparison a rescaling is required.

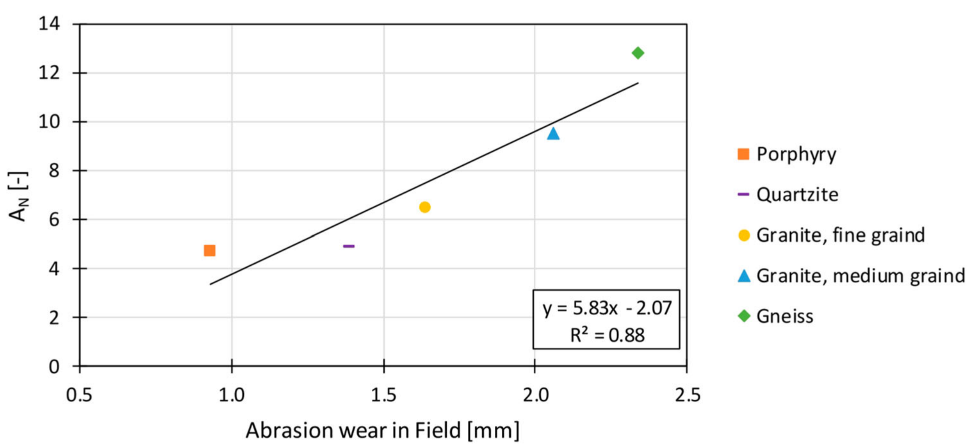


Figure 5. The relation between Nordic abrasion value (AN) and abrasion wear in field, for five different types of mineral aggregate types. Redrawn from Jacobson and Wågberg (2007).

For the Prall sub-model, the corresponding equation is:

$$\mathrm{RW} = 0.32 + 0.04 \cdot A_P \tag{2}$$

where A_P is the Prall abrasion value [cm^3], determined according to CEN (2016), which is related to the asphalt mass properties, compared to only the mineral aggregate properties as in the Mineral aggregate sub-model. The model is valid for A_P between 13 and 46 cm^3, $R^2 = 0.75$. This is presented in Figure 7 (Jacobson and Wågberg 2007).

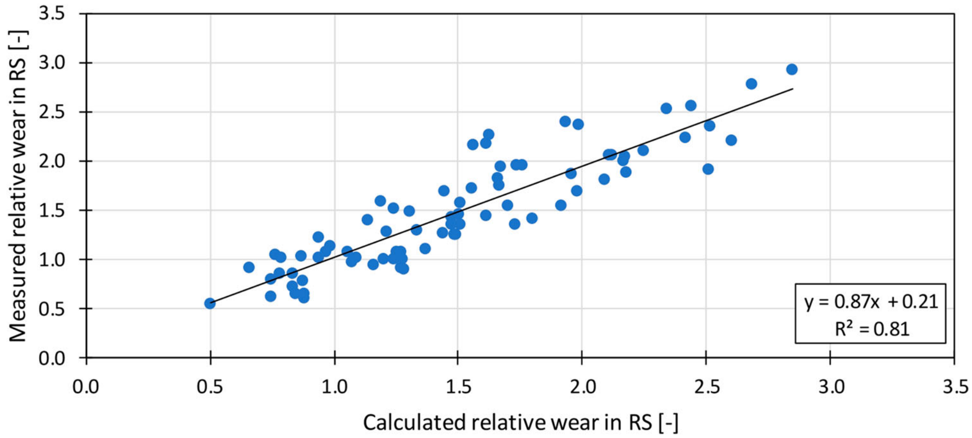


Figure 6. Description of the multiple regression model (using Equation (1)) ability to predict the relative abrasion wear (RW) obtained in the RS.

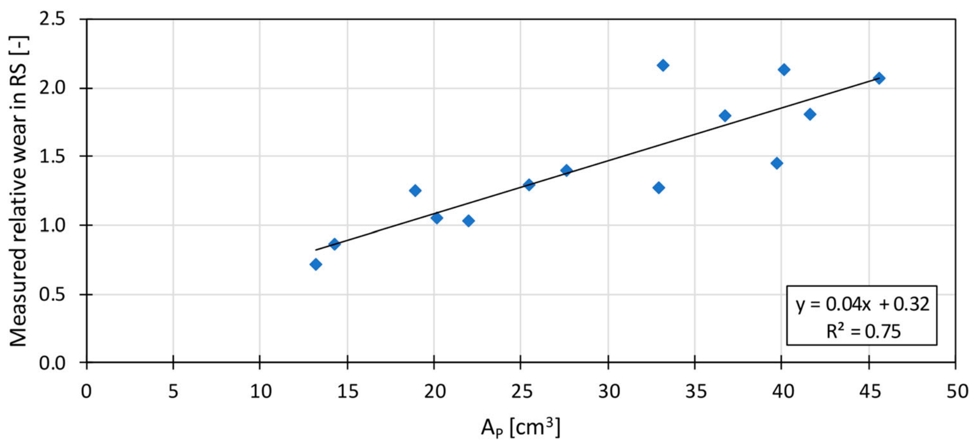


Figure 7. The relation between relative abrasion wear (RW) measured in the RS and the Prall abrasion value. Redrawn from Jacobson and Wågberg (2007).

Material factor

A material factor is calculated, taking into account the speed, usage of de-icing and type of studs, as well as the relative wear, calculated with either of the two sub-models. The material factor f_M [–] is calculated by:

$$f_M = \mathrm{RW} \cdot f_v \cdot f_s \cdot f_{\mathrm{st}} \tag{3}$$

where RW is the relative abrasion wear [–] based on either of the two sub-models, f_v is the speed factor [–], given in Table 1, f_s is the de-icing factor [–], given in Table 1 and f_{st} is the stud calibration factor [–], empirically set to 0.75.

Since the development of the model, more speed limits have been introduced in Sweden. An interpolation was thus performed for f_v in Table 1, to allow using more speeds, giving:

$$f_v = 0.0143 \cdot v - 0.0775, \quad R^2 = 0.99 \tag{4}$$

where v is the speed [km/h].

Table 1. Material factor for speed and de-icing.

Factor speed		Factor de-icing	
Speed [km/h]	f_v [–]	Salt [–]	f_s [–]
50	0.65	Yes	1.0
70	0.90	No	0.8
90	1.20		
110	1.50		

Abrasion wear distribution

The second part of the model refers to the lateral wander distribution of the abrasion wear across the traffic lane. The model assumes that the lateral traffic wander follows a normal

Table 2. The different type sections available, together with their corresponding road type, lane width and the standard deviation of the lateral wander of vehicles for different road types.

Type section	Road type	Lane width [m]	Standard deviation of the lateral wander [m]
1	7 m	3.5	0.275
2	9 m	3.75	0.350
3	13 m	6.5	0.450
4	Wide Lanes	6.5	0.500
5	Highway	4	0.250
6	Tunnel	4	0.225
7	2 + 1 Road	3.25	0.200
8	Extra Narrow Lanes	3	0.180

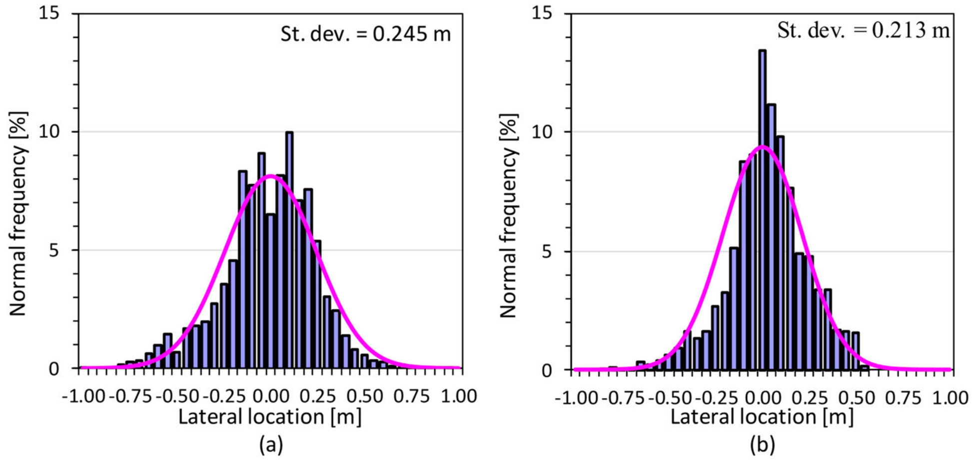


Figure 8. Two examples of measured lateral wander of traffic: (a) 4 m lane width highway. (b) 3.25 m lane width on a 2 + 1 road. From Erlingsson *et al.* (2012).

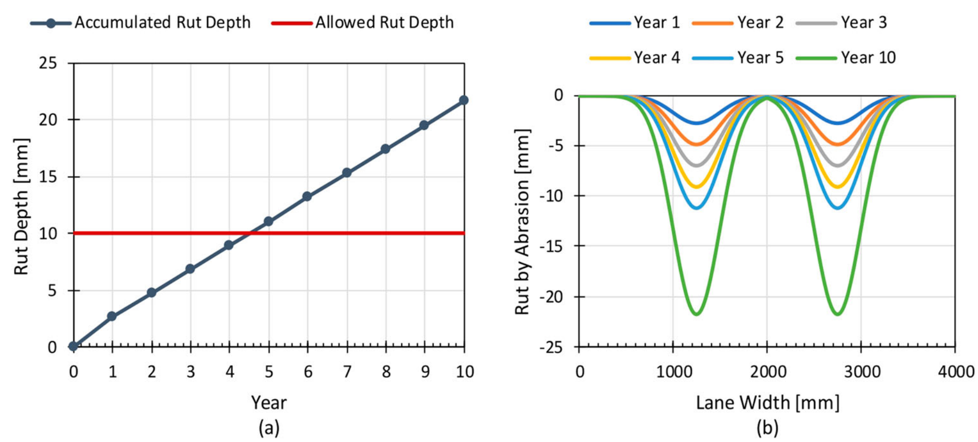


Figure 9. Example of results from the abrasion wear model for the motorway E6 Uddevalla 4 using the Mineral aggregate sub-model. (a) Abrasion wear development and allowed wear depth from user input. (b) The transverse abrasion wear profile over a fixed lane width. Similar graphs can be produced for the Prall sub-model.

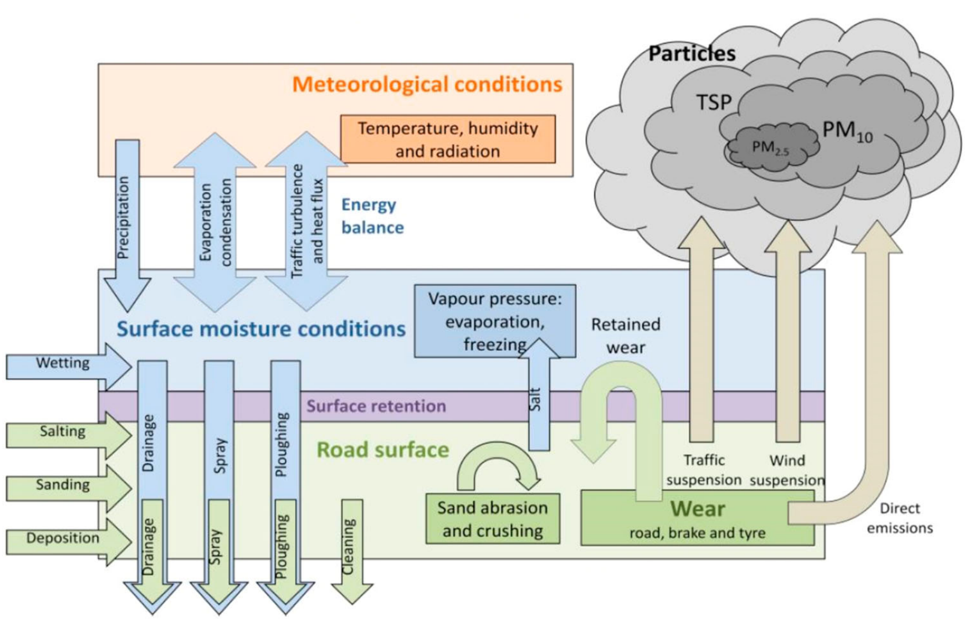


Figure 10. Schematic outline of the NORTRIP model. Source: Denby *et al.* (2013b).

distribution:

$$f(x) = \frac{1}{2.506 \cdot \sigma} e^{-0.5\left(\frac{x}{\sigma}\right)^2} \quad (5)$$

where $f(x)$ is the normal distribution frequency function, σ is the standard deviation of the lateral wander for vehicles [mm] for selected road type section, given in Table 2, and x is the fixed position [mm] (frequently plotted in steps ranging from $-1500 < x < 1500$ in steps of 50 mm). Examples of measured lateral wander on two road facilities are given in Figure 8 (Erlingsson *et al.* 2012).

The amount of studded tyre traffic at each point per year in the transverse profile, $T(x)$ [vehicles/year] is calculated as:

$$T(x) = f(x) \cdot x_d \cdot \mathrm{AADT}_L \cdot W_p \cdot \frac{\mathrm{SST}}{100} \quad (6)$$

where $f(x)$ is the normal distribution frequency function from Equation (5), x_d is the bin width (usually fixated to 50 mm), AADT_L is the average annual daily light traffic in user-selected lane [vehicles/day], W_p is the wear period defined as days with studded tyre share > 5% and SST is the average vehicle share with studded tyres of the season [%].

Under current Swedish legislation (TSFS 2009:19, 2013:63), W_p can, under normal circumstances, vary between 121 and 197 days. The 121 days (1 December – 31 March) is the period for which use of all types of winter tyres is mandatory and 197 days (1 October – 15 April) is the maximum number of days during which studded tyres are allowed.

The wear per year at each point, $W(x)$ [mm/year] is calculated by:

$$W(x) = \frac{T(x) \cdot f_M \cdot W_{\mathrm{veh}}}{x_d} \quad (7)$$

where $T(x)$ is the number of vehicles at x from Equation (6) [vehicles/year], f_M is the material factor from Equation (3) [–], W_{veh} is the abrasion wear per vehicle based on measured wear during earlier validations [mm/vehicle] (currently set to 0.00102 mm/veh) and x_d is the bin width (usually fixated to 50 mm).

The average profile wear (APW) is then calculated as the sum of wear over the full width for two tracks, while the maximum track wear (MTW) is calculated as the maximum wear depth in one track. Neither APW or MTW include the initial wear, which is handled separately.

An adjustment is made in the model for the initial abrasion wear that occur during the first winter season after the construction due to the combination of residual material present after construction and initial removal of the weaker components of the surfacing. This adjustment is done by using a high number of vehicles, currently estimated to the first 300,000 vehicles with studded tyres. This calculation is similar to the calculation of studded tyre traffic and the abrasion wear in each point (Equations 6–7).

For the track wear prediction, a total initial track wear of 0.5 mm is assumed for pavements where $\mathrm{MAS}_4 > 60\%$, otherwise a total initial track wear of 1.0 mm is assumed. For the Prall sub-model, an initial wear of 0.5 mm is assumed for SMA, while 1.0 mm is assumed for DAC. For both models, it

Table 3. Field data used for calibration.

Road and location	Wearing course[a]	A_N [–]	MAS_4 [w.%]	D_{max} [mm]	A_p [cm³]	Constr. year	No. seasons[b]	No. datapoints	Speed [km/h]	AADT [veh./day]	AADT_L[c]	Type section	Measured lane	De-icing	W_p [days]	SST [%]	MAPW[d] [mm/year]	AMTW[d] [mm/year]
E4 Uppsala	1 GAR16	5	78	16	–	2011	3	4	110	16,827	70%	Highway	Rightmost	Yes	180	65	0.87	1.59
	2 GAR16	5	78	16	–	2011	3	4	110	16,827	70%	Highway	Rightmost	Yes	180	65	0.89	1.80
	3 SMA16	5	77	16	–	2011	3	4	110	16,827	70%	Highway	Rightmost	Yes	180	65	0.36	0.81
E6 Uddevalla	1 SMA16	5.5-9	74	16	20	2006	4	16	110	11,301	70%	Highway	Rightmost	Yes	180	69	0.32	0.56
E6 Mölndal	1 GAR11	7	72	11	–	2011	3	3	80	31,802	70%	Highway	Rightmost	Yes	180	63	0.68	1.48
	2 SMA11	7	71	11	–	2011	3	6	80	31,802	70%	Highway	Rightmost	Yes	180	63	0.59	1.29
E4 Södertälje	1 SMA16	6	74	16	>30	2004	2	2	110	31,922	70%	Highway	Rightmost	Yes	180	62	0.85	2.33
E4 Pershagen	1 SMA16	<7	74	16	26	2005	2	2	110	28,011	70%	Highway	Rightmost	Yes	180	62	1.07	2.69
	2 SMA16	<7	75	16	–	2006	1	1	110	28,011	70%	Highway	Rightmost	Yes	180	62	0.98	2.25
Rv 229	1 SMA16	<7	74	16	28	2005	2	2	70	34,224	70%	7 m	Rightmost	Yes	180	62	0.82	2.11
Rv 73	1 SMA16	<7	76	16	27	2005	2	2	90	43,446	70%	7 m	Rightmost	Yes	180	62	1.16	3.14
	2 SMA16	<7	75	16	24	2006	1	1	90	43,446	70%	7 m	Rightmost	Yes	180	62	0.93	2.30

[a]GAR = GAp graded Rubber asphalt.
[b]Not including first season, thus not including initial abrasion wear.
[c]Estimated share of traffic from the AADT, in the investigated lane used in model calculations.
[d]MAPW is the Mean Average Profile Wear and AMTW is the Average Maximum Track Wear. The averages are calculated from all available years of measured wear rate, not including the initial season, thus not including the initial abrasion wear.

is also calculated how many years this total initial track wear (0.5 or 1.0 mm) takes place, t_i [years] by calculating:

$$t_i = \frac{V_i}{\mathrm{AADT}_L \cdot W_p \cdot \frac{\mathrm{SST}}{100}} \quad (8)$$

where V_i is the number of initial vehicles set at 300 000, AADT_L is the average annual daily traffic in user-selected lane [vehicles/day], W_p is the wear period defined as days with studded tyre share > 5%, SST is the share studded tyre [%].

The track depth for a given year is then calculated based on different criteria and is done for a period of 20 years. If $t_i \leq 1$, d_t [mm/year] is 0.5 or 1.0 depending on the type of surface (SMA or DAC) and takes place during the first winter season. If $t_i > 1$, the initial wear (0.5 or 1.0 mm) is proportionally distributed over the appropriate amount of winter seasons, e.g. with a t_i of 2.3 a 43.5% of the initial wear (1/2.3) takes place during year one and two respectively and the remaining part 13% (0.3/2.3) during the third winter.

After calculation of the magnitude of the initial track wear for each year, it is summarised with the maximum track wear rate for each year, and the cumulative sum for each time step (one year), which then is illustrated in a graph, e.g. in Figure 9(a).

For profile wear, the initial profile wear from the 300,000 vehicles is distributed using Equation (6). The abrasion wear profile is then drawn using the sum of APW for the year of interest with the initial profile wear, which is then illustrated in a graph, e.g. in Figure 9(b).

Model output

In extension to the above-mentioned outputs, the abrasion wear model also can give the user the Specific Abrasion

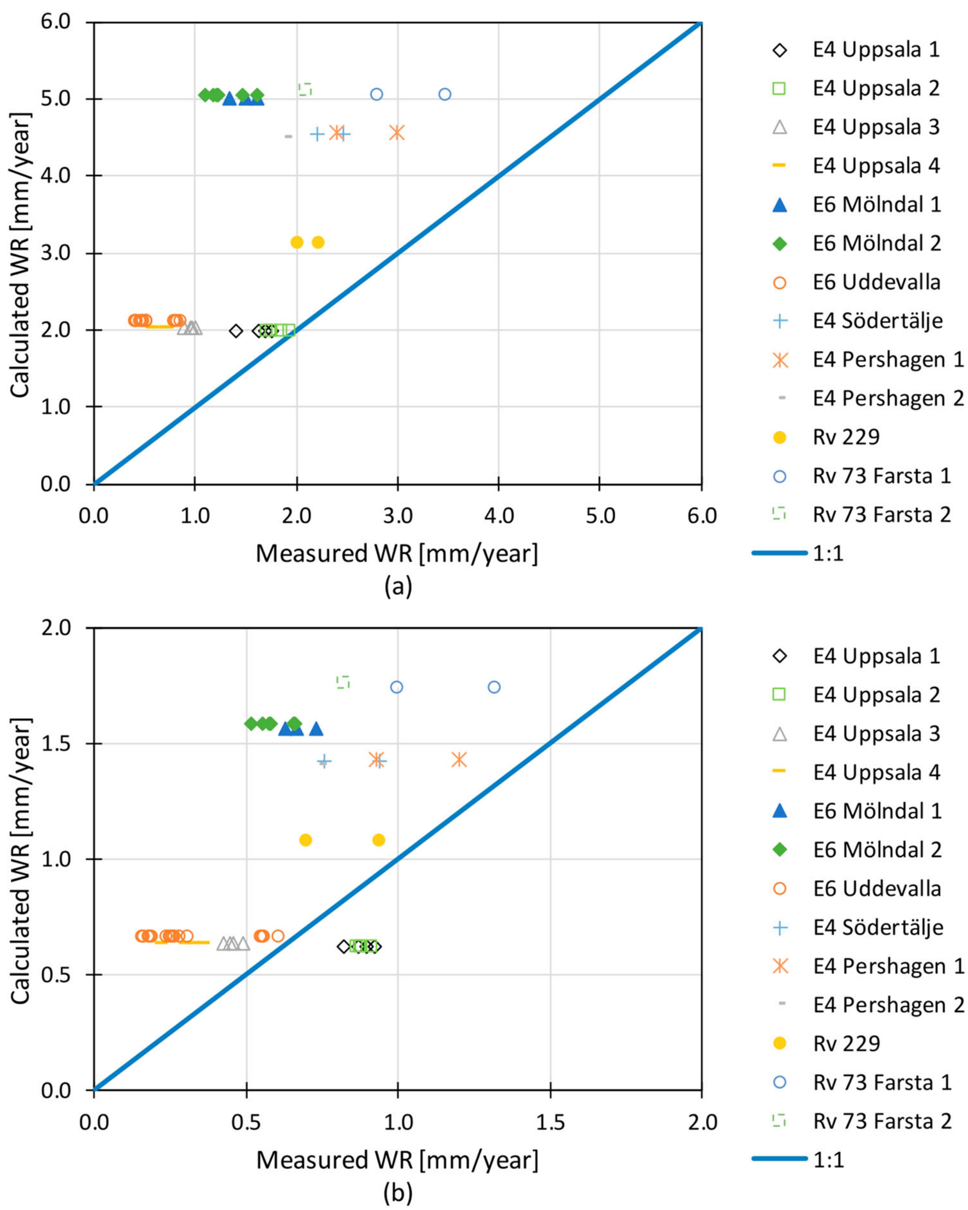
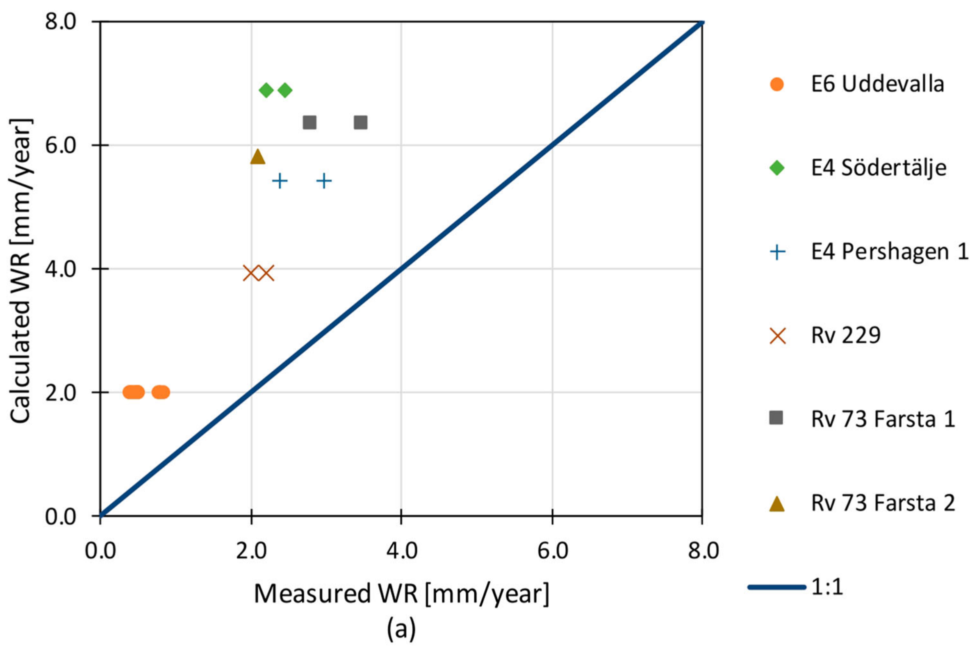


Figure 11. Wear Rate for the Mineral Aggregate sub-model, with no initial abrasion wear: (a) Maximum Track Wear, (b) Average Profile Wear.

(SA) [g/vehicle and km], defined as 'The amount of pavement, expressed in grams, which a vehicle with studded tyres wears on a stretch of one kilometre' (Jacobson and Wågberg 2007). Other available outputs include the worn amount of pavement per 100 m road stretch [tonnes] as well as the worn amount of pavement per 100 m road stretch over the total lifetime [tonnes] and the adjusted lifespan [years]. The adjusted lifespan is usually limited to 20 years. Also available is the abrasion wear rate [mm/year], the maximum rut depth [mm] at user specified year, calculated service life [year] and the yearly cost per road surface area [SEK/m^2]. The final possible outputs are given as graphical presentations, e.g. in Figure 9 where the road E6 Uddevalla 4 was used.

NORTRIP particle emission model description

The wear model using the Mineral aggregate sub-model is part of the NORTRIP model (Denby and Sundvor 2012, Denby *et al.*, 2013a, 2013b). Denby *et al.* (2013b) describe how most emission models deal with non-exhaust emissions by using emission factors only related to driven km and are therefore unable to assess mitigation strategies and properly account for weather effects, since the process of road dust accumulation on road surfaces is not included. To help air quality managers in their work, the NORTRIP model was developed to allow studying the impact of policies and mitigation measures on the non-exhaust PM_{10} emissions. To study this phenomenon, the model was developed to lay emphasis on the road surface



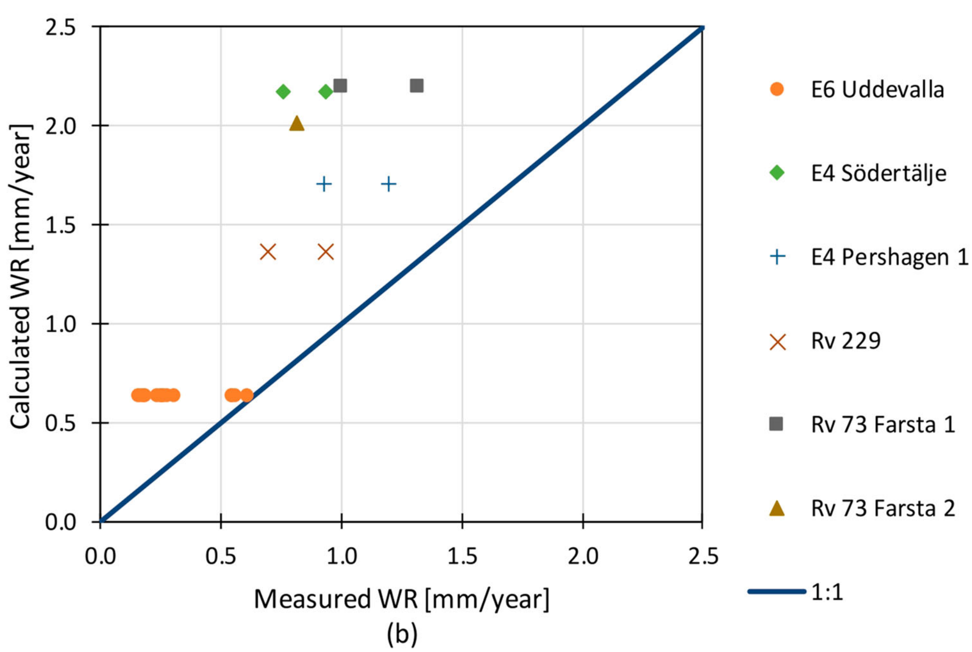


Figure 12. Wear Rate for the Prall sub-model with no initial abrasion wear: (a) Maximum Track Wear (b) Average Profile Wear.

impact on non-exhaust PM_{10} from road traffic (e.g. contribution of abrasion wear, surface wetness impact on road dust retention, etc.). A schematic overview of the model and the different processes that are included is given in Figure 10.

The contribution of pavement abrasion wear to PM_{10} is calculated using the RW of the Mineral aggregate sub-model (RW is known as h_{pave} in NORTRIP). The NORTRIP model requires extensive background information regarding meteorological, traffic and dust abatement (e.g. road cleaning, dust binding) conditions. The output of road abrasion wear is then described for light vehicles with studded tyres by (Denby and Sundvor 2012; Denby *et al.*, 2013b):

$$W_{pw} = W_{0,pw} \cdot \mathrm{RW} \cdot \left(\frac{V_{veh}}{V_{ref,pw}}\right)^{a_{wear}} \quad (9)$$

where W_{pw} is the road abrasion wear per vehicle [g/km/veh], $W_{0,pw}$ is the basic road abrasion wear parameter [g/km/veh] set to 2.88 g/km/veh, V_{veh} is the vehicle speed [km/h], $V_{ref,pw}$ is the reference speed for road abrasion wear [km/h] set to 70 km/h and a_{wear} is the power law dependency [−] set to 1.0 (a power law dependency is included in the model but is currently set to unity for future proving reasons).

Field data for abrasion wear model validation

Data on the field road sections, used for model calibration, have been compiled from former research projects (Göransson 2009, Carlsson 2015, Swedish Transport Administration, 2016a, 2016b), and consists primarely of different types of SMA pavements, which are commonly used in Sweden. All relevant technical and traffic data are presented in Table 3. Field data were measured using the earlier described laser profilometer.

Evaluation methods

Evaluation of model validity

The evaluation of the model was done by comparing the measured abrasion wear rates and the calculated wear rates for the road sections given in Table 3. The predicted abrasion wear is based on the year of construction, which is compared to the measured abrasion wear. The measured abrasion wear rates are both the mean profile wear rate (the mean abrasion over a full profile) as well as the mean track wear rate (the mean track abrasion for both tracks). These are compared to the mean profile wear rate and to the maximum track wear rate calculated by the model. In limited cases, engineering judgement was employed in case of missing data, e.g. the use of regional data for studded tyre usage (Swedish Transport Administration 2016a), traffic volumes or distribution of traffic between different lanes.

The corresponding abrasion wear rates predicted by the model were plotted against the measured abrasion wear rates for the same period (see Figures 11 and 12). Also, the measured abrasion wear rates for the different roads for each year were plotted against the predicted abrasion wear rates. These abrasion wear rates were thereafter used to calculate a suitable reduction factor for the calibration of the model.

Abrasion wear model results and discussion

Evaluation of model validity

The results for the Mineral aggregate sub-model are presented in Figure 11 and the results for the Prall sub-model is presented in Figure 12. For most objects both sub-models overestimate the calculated WR, both regarding MTW and APW. This indicates that a new correction is required to adjust to the observed abrasion wear. This result is likely affected by the fact that the abrasion wear model was developed using old tyre types, giving reason to believe that newer regulations and the developments following them are at least partly responsible for the overestimation, but also affected by the lack of precise historical data. Two road sections consist of GAR16 (Gap Graded Rubber asphalt with a nominal maximum aggregate size of 16 mm, sections E4 Uppsala 1 and 2) surfacings and this type of surface layer was not included in the initial model development. Despite this, these two sections show modelled maximum track wear rates close to their measured values, while the average profile wear rates are underestimated. Although, more new data including also new surfaces would be of preference in order to allow for proper use of the model on surface layers that were not originally included from the start.

A comparison of the two sub-models, presented in Figure 13, shows that, based on the available data points, the Prall sub-model gives a higher predicted abrasion wear for both MTW and APW.

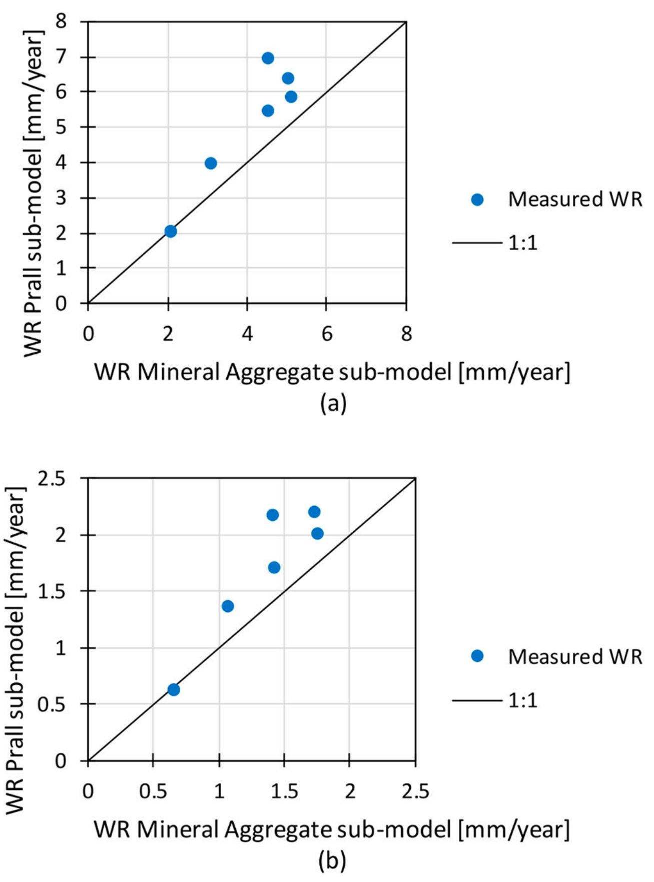


Figure 13. Comparison between calculation (prediction) based on the Mineral aggregate and Prall sub-models for: (a) MTW, (b) APW.

Sensitivity analysis

A sensitivity analysis was performed for the maximum and minimum values allowed for the different models. This evaluation was done by using one of the test roads and changing one parameter at a time to the maximum and minimum levels for which the model is valid or, in cases where no upper or lower limits existed, assumptions were made to reasonable maximum versus minimum levels.

The sensitivity analysis of the different required data and their effect on the calculated abrasion wear rate are presented in Figure 14. In the sensitivity analysis, the highest and lowest limits were assumed to the highest and lowest values available in the dataset used for the model development. A lower limit of 50% of the measured traffic was assumed for the investigated lane and the higher limit was assumed to be 100% of the maximum measured traffic. It was also assumed that the wear period (W_p) ranged between the time span of 121–197 days as stated earlier. For SST, the uppermost and lowest values assumed were based on data from the Swedish Transport Administration (2016a). For the Prall value (A_P), the Prall sub-model was used.

The results show that different parameters have a large effect on the results. In common for both APW and MTW, the traffic parameters SST followed by the share of $AADT_L$ and the time parameter the wear period showed a high variation in the resulting abrasion wear rate. Regarding MTW, for both models the type section can have a large impact, although it is less likely to be based on a less reliable input since the lane width usually is easier to assume and control rather than, for example, the SST. The APW was, as expected, not influenced by the section type. The section type determines the lateral wander (see Table 2, standard deviation), which will affect the shape of the wear profile (e.g. Figure 9(b)). Given constant traffic, an increased lateral wander will increase the width of the track, causing a decreased maximum wear depth (MTW), while keeping the profile area constant, and thus also keeping the APW constant. For the Mineral aggregate sub-model, as seen, the pavement parameters A_N followed by D_{max} and MAS_4, results in a large impact on the abrasion wear rate, based on the maximum and minimum values used in the model. A similar result was seen for the Prall sub-model where the pavement parameter A_P has a high impact on the resulting abrasion wear rate.

Calibration of the abrasion wear model

The two sub-models were calibrated with the average of the measured data shown in Figures 11 and 12, giving a suggested reduction factor of 56% for the Mineral aggregate model and 51% for the Prall model, respectively. This factor can be implemented as an extra reduction factor in Equation (3).

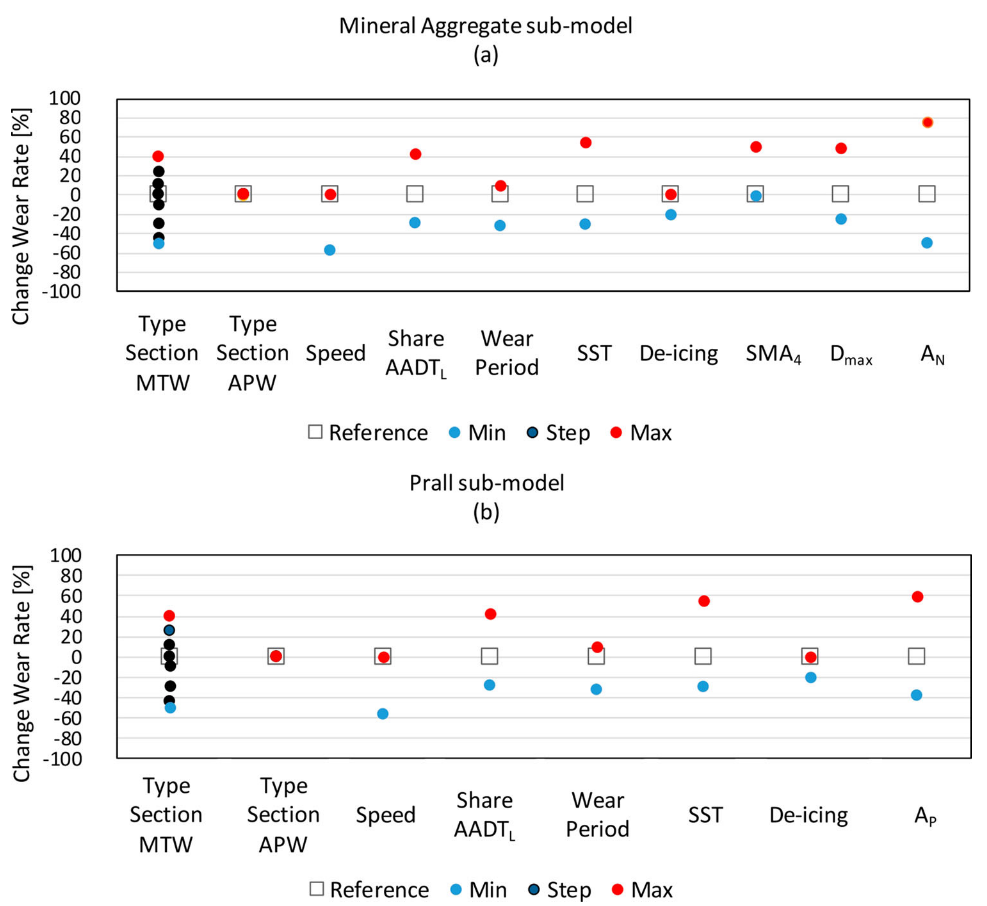


Figure 14. Single parameter sensitivity analysis of the motorway E4 Pershagen 1. (a) Displays the Mineral aggregate sub-model. (b) Displays the Prall sub-model. For both (a) and (b), for all cases, blue marks the lowest possible input data either deemed reasonable or the lowest value used when developing the model. Similarly, red shows the maximum possible input data. For the type section, black marks the other type sections available. The type sections are defined in Table 2. The reference values are given in Table 3.

Implementing these reduction factors for the data in Table 3 gives the result presented in Figures 15 and 16. As can be seen, a better fit was achieved with the reduction factors, especially for the Prall sub-model. For the Mineral aggregate sub-model, a better fit was still achieved, although the same test section as before (E4 Uppsala 1–2) stands out the most, regarding the average profile wear, while the maximum track wear now instead is underestimated in this case.

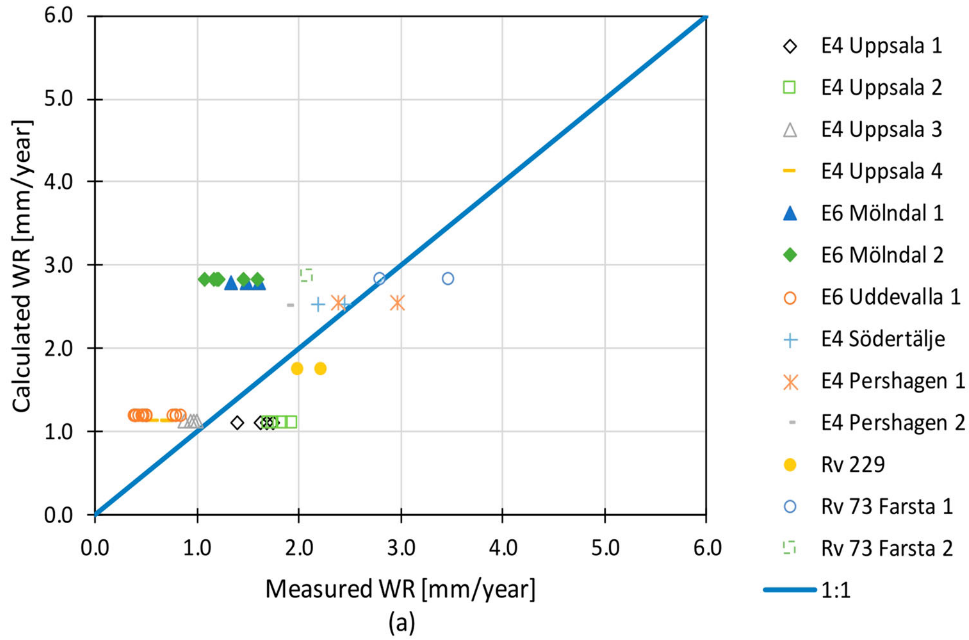
Impact on NORTRIP emission model

To investigate the impact on NORTRIP due to a reduction of the RW, the PM_{10} concentration as well as the emission factor was modelled for the following cases where the current RW (Equation (1)) is decreased by:

(1) 0%
(2) 40%
(3) 50%
(4) 60%

A dataset for Hornsgatan in central Stockholm, Sweden, for the winter and dust season 2006/2007 was used, giving an $R^2 = 0.58$ for PM_{10} data, using the default settings.

The calculated emission factors and particle concentrations are presented in Figure 17. As can be seen, the mean concentration as well as the mean emission factor were, as expected, reduced when the abrasion wear was reduced. The difference between the observed and the modelled emission factors increased in all cases. This implies that other aspects in NORTRIP instead of the abrasion wear must explain the difference



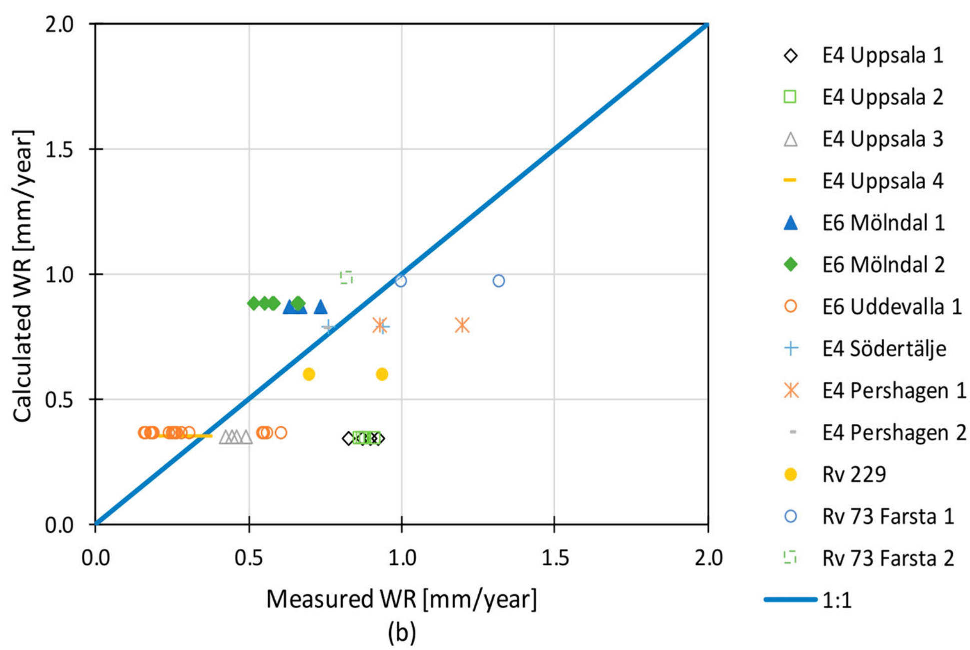


Figure 15. Illustration of abrasion wear rate after implementation of the calibration factors for the Mineral aggregate sub-model: (a) Maximum Track Wear, (b) Average Profile Wear.

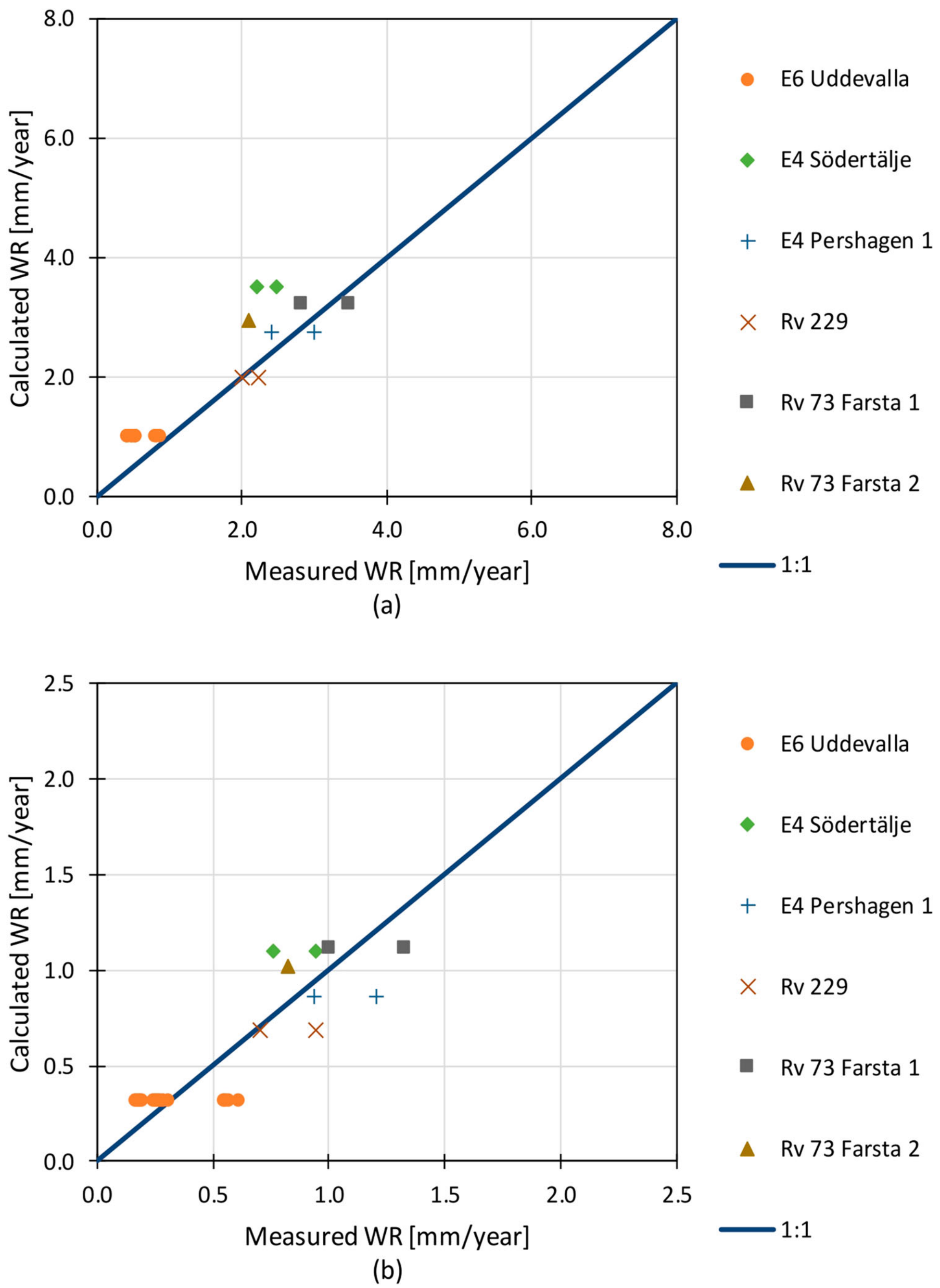


Figure 16. Illustration of Wear Rate after implementation of the calibration factors for the Prall sub-model: (a) Maximum Track Wear, (b) Average Profile Wear.

in observed and modelled emissions to compensate for the lowered contribution from abrasion wear of pavements. These new findings could further improve the fundamental understanding of road dust emissions.

Conclusions and final remarks

The paper describes a studded tyre abrasion wear model developed and used in Sweden. The model is used to, based on pavement and traffic parameters, predict the contribution of abrasion wear to the total rut depth of pavements.

Due to the new circumstances from tyre and road surfacing development, it is important to adjust the abrasion wear model to the new circumstances through calibration. Both prior and after calibration, the model was found to give valuable input, both regarding abrasion wear rates for maintenance planning and the understanding of emissions of abrasion wear particles to air. The results also showed that newer types of surfacings can give similar or different results compared to what has been observed and thus new surfacing materials need measured data of abrasion wear to be included in the model for more general application.

The sensitivity analysis shows that the input data (e.g. pavement data) can have a large impact on the results. The proposed change in the model by using calibration factors (56% and 51% for the Mineral aggregate model and the Prall model respectively) was found to improve the abrasion wear predictions, while also resulting in a reduction for both the mean emission

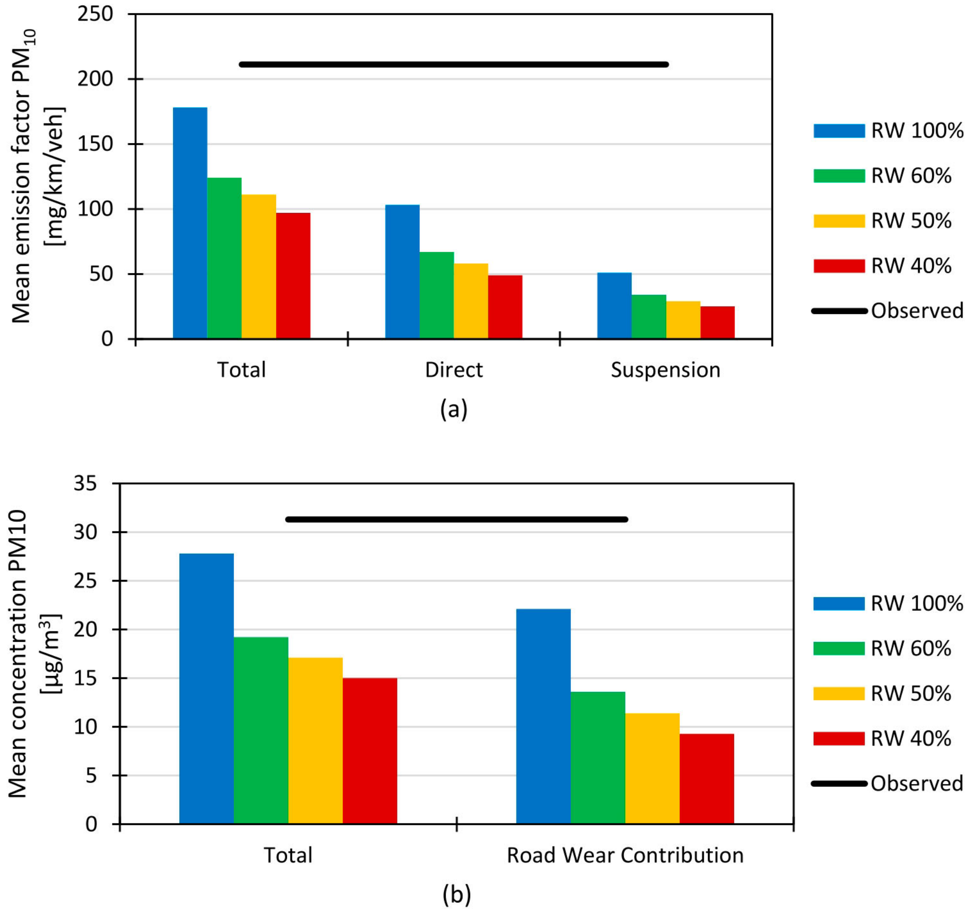


Figure 17. Changes in NORTRIP due to decreased abrasion wear for Hornsgatan, Stockholm for the year 2006/2007. (a) Changes in mean emission factor for PM10. (b) Changes in mean concentration for PM10.

factors and the mean concentration of PM_{10} in NORTRIP, improving the understanding of abrasion wear particle emission.

Further work should focus on gaining access to a larger quantity of measured data, mainly new data for present design of both tyres, studs and road surface materials, but also trying to access historical data for a more detailed evaluation of the model. The rapid development of tyre and pavement techniques and standards imply a need to perform a new regression analysis of road abrasion wear. Further, improved usability could be attained by including yearly development of the traffic and share of studded tyres (SST) in the model.

The connection between the particle emission model NORTRIP and this abrasion wear model should be further evaluated to improve both models. Running both the NORTRIP model and the road abrasion wear model in parallel at the same sites would give important insights into results for both areas. In continuation, given an updated regression analysis of the RW (Relative Wear, the regression in common for both models), the NORTRIP emission model should be updated regarding road wear contribution to PM_{10}.

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Disclosure statement

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