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PROGRESS TOWARDS TRAFFIC INDUCED ROAD DUST AND SALT EMISSION MODELLING: MODEL DEVELOPMENT WITHIN NORTRIP

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Abstract: Non-exhaust traffic induced emissions are a major source of particle mass in most European countries. This is particularly important in Nordic and Alpine countries where winter time road traction maintenance occurs, e.g. salting and sanding, and where studded tyres are used. Modelling these emissions is a challenging task as they are sensitive to environmental factors such as road surface moisture as well as road maintenance activities (salting and sanding) and tyre and vehicle types. The ability to model these emissions is desirable as this provides the potential for more effective road management, improved assessment of mitigation strategies for reducing emissions and can help quantify the impact of salting and sanding activities. These are all important applications relevant to the European AQ Directive. The Nordic based project NORTRIP is building upon existing road dust emission models, combined with field and laboratory measurements, to develop a more comprehensive and generalised process based model description of the non-exhaust emissions, with emphasis on the contribution of road wear, salt and sand to the emissions. In this paper we present the current status of the modelling, briefly describing the processes and their parameterisations. The performance of the model is illustrated using two example applications from Norway and Sweden and future developments are discussed.

Key words: *Road dust, road salting, suspension, air quality, emissions, modelling*

INTRODUCTION

Non-exhaust traffic induced emissions are a major source of particle mass in most European countries. This is particularly important in Nordic and Alpine countries where winter time road traction maintenance occurs, e.g. salting and sanding, and where studded tyres are used. Current models used for predicting road dust emissions have a number of limitations, the most important of which is that the models are generally based on local measurements and conditions, neglecting a range of processes that would be important to describe the emissions. There is a need for a more generalised approach that can be applied over a wider range of environments and that are more process based. The model from Omstedt et al. (2005) has been shown to produce good results under Swedish conditions (Omstedt et al., 2011) and, with some adaptations, also under Finnish conditions (Kauhaniemi, 2011). The model contains some of the basic physical processes. The major drawback of the Omstedt model is that it is empirically fitted to measurement data and lacks a number of important process descriptions, which are essential if effective management of these emissions are to be carried out, e.g. dependence on vehicle speed, studded tyre share. However, it does include a number of important features, such as the mass balance of road dust loading and a road surface moisture model that could be used to predict surface conditions. To address some of the short comings of this model a more generalised and process based model was developed by Berger and Denby (2011). This model based emissions on the wear rates themselves and included dependencies on vehicle type, studded tyre share and vehicle speed. As such it was not dependent on local measurements to obtain model results. However, this model lacked a physically based road surface moisture description and was found to produce acceptable results only under dry conditions.

The model described in this paper (GRD-2; Generalised Road Dust emission model - 2) is based on these two approaches, taking elements from both and including new processes and parameterisations. The aim is to represent the most important processes related to both road dust generation and road surface moisture, particularly those processes that may be important for describing and reducing these emissions. The model is divided into two coupled sub-models:

1. **Road dust sub-model:** This predicts the road dust and salt loading through a mass balance approach as well as the emission through direct wear and through suspension of these loadings. Mass is deposited on the surface by wear (road, tyre and brake) and by the addition of salt and sand. Mass is removed by suspension, drainage, splash/spray and by road maintenance activities.
2. **Road surface moisture sub-model:** This determines road surface conditions (water and ice) essential for the prediction of suspension from the road surface. A surface mass balance approach is also applied here, including evaporation/condensation, drainage, splash/spray, precipitation, refreezing and road maintenance activities. The impact of salt on the hygroscopic properties of the surface is also to be addressed.

The major characteristics of the model are outlined in the next two sections of this paper and an overview of the model concept is provided in Figure 1.

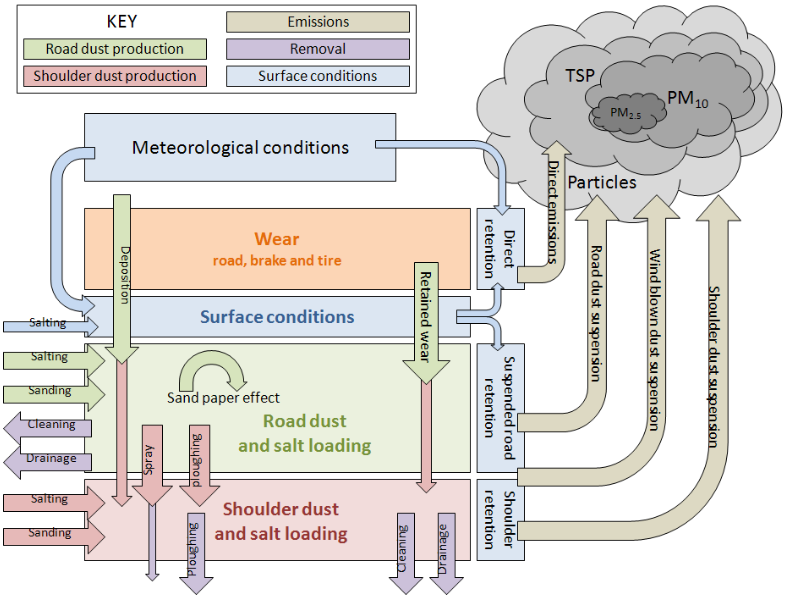

Figure 1. Schematic outline of the Generalised Road Dust emission model described in this paper.

ROAD DUST GENERATION, LOADING AND EMISSION

The road dust model makes use of total wear rates as the basis for determining direct emissions of particles and for accumulating dust (loading) on the road surface. Direct wear sources are the road surface itself (in Nordic countries this is mostly the result of the winter time use of studded tyres), the vehicle tyres and from brake wear. A defined proportion of these wear sources are directly emitted to the air (~25%) in a range of size fractions and the rest is accumulated on the road surface. In addition to the contribution from wear sources, the model includes the surface accumulation of mass from salting and sanding activities. The build up of mass on the road surface is defined separately for dust and salt contributions. The following processes and sources concerning road surface dust loading are described in the model. The parameters in brackets refer to Equations 1 – 6.

- Total wear of road, brakes and tyres is based on the loss of mass from these sources, allowing for the impact of different tyres and pavement types on the wear rates (WR_{wear}). Road wear, for example, is dependent on tyre type, vehicle type, road surface type and vehicle speed.
- A proportion of the total wear ($f_{0,dir\text{-}wear}$) is allowed to be emitted directly to the air and a portion is deposited on the surface ($1\text{-}f_{0,dir\text{-}wear}$). This is distributed to both the road and shoulder surfaces ($f_{retention\text{-}shoulder}$).
- Dust loading ($M_{dust\text{-}road}$) is suspended ($S_{sus\text{-}road}$) at a rate proportional to the dust loading, the traffic volume (N) and a prescribed suspension factor ($f_{sus\text{-}road}$). This suspension factor is dependent on vehicle type (*he*avy, *li*ght), vehicle speed (V_{veh}) and tyre type (*st*udded, *wi*nter, *su*mmer). Most importantly the suspension is controlled by the surface moisture retention factor ($f_{q,road}$), predicted by the surface moisture model.
- Emissions through suspension ($E^{x}_{sus\text{-}road}$) are distributed into different size classes x. The suspension emissions are directly related to the suspension sink ($S_{sus\text{-}road}$).
- Other production terms for the dust loading include generation through abrasion ($P_{sandpaper}$), application through sanding ($P_{sanding}$) and deposition to the surface from the atmosphere ($P_{deposition}$).
- Sink terms ($S_{dust\text{-}road}$) in the equation include a number of processes in addition to suspension ($S_{sus\text{-}road}$). These include windblown dust, drainage, cleaning, snow removal (ploughing) and water spray processes.

An example, for road dust wear, of the model description is provided below in Equations 1 - 6. The complete set of equations is more extensive than provided here. The road dust mass balance is given by

$$\frac{\partial M_{dust-road}}{\partial t} = P_{dust-road} - S_{dust-road} \quad . \tag{1}$$

In this equation the production ($P_{dust\text{-}road}$) and sink terms ($S_{dust\text{-}road}$) are given as:

$$P_{dust-road} = P_{retention-roadwear}[1 - f_{retention-shoulder}] + P_{sandpaper} + P_{deposition} + P_{sanding} \tag{2}$$

$$S_{dust-road} = S_{sus-road} + S_{wind} + S_{drainage} + S_{cleaning} + S_{ploughing} + S_{spray} \tag{3}$$

Of these, the retention of road wear to the surface is described by

$$P_{retention-roadwear} = \sum_{t=st,wi,su}^{tire} \sum_{v=he,li}^{vehicle} WR_{roadwear}^{t,v} \cdot [1 - f_{0,dir-roadwear}^{t,v} \cdot f_{q,road}] \quad (4)$$

and the suspension of road dust is given by

$$S_{sus-road} = M_{dust-road} \cdot \sum_{t=st,wi,su}^{tire} \sum_{v=he,li}^{vehicle} N^{t,v} \cdot f_{sus-road}^{t,v} \cdot f_{q,road} \quad (5)$$

The emission of suspended road dust ($E^{x}_{sus-road}$) in the size class x (e.g. < 10 μgm^{-3}) is directly related to the suspension sink and is given by:

$$E_{sus-road}^{x} = S_{sus-road} \cdot f_{PM}^{x} \quad (6)$$

Here f^{x}_{PM} is the fraction of the suspended PM in the size class x. In this way the model consistently follows the production and loss of mass related to the suspension. Various parameterisations are employed for the different production and sink terms in Equations 2 and 3.

ROAD SURFACE MOISTURE CONDITIONS

An essential part of the model is the description of the surface moisture, which is required to determine the retention of particles on the surface. So, in addition to the mass balance equation for road and shoulder dust and salt (Equation 1), a mass balance equation governing liquid water (g_{road}) and snow/ice (s_{road}) content on the road and shoulder surface is employed. In Equations 7 – 9 the mass balance equations for the road surface liquid water are provided. They include processes such as precipitation, surface snow melting, condensation, drainage, removal by splash and spray, evaporation and conversion to ice through freezing. A similar set of equations is used for snow/ice on the road and shoulder surface.

$$\frac{\partial g_{road}}{\partial t} = P_{g,road} - S_{g,road} \quad (7)$$

$$P_{g,road} = P_{g,rain-road} + P_{g,snowmelt-road} + P_{g,wetting-road} + P_{g,condens-road} \quad (8)$$

$$S_{g,road} = S_{g,drain-road} + S_{g,spray-road} + S_{g,evap-road} + S_{g,freeze-road} \quad (9)$$

Of these terms the evaporation sink ($S_{g,evap-road}$) and condensation production ($P_{g,condens-road}$) rates are very important. To determine these, a road surface energy balance model is applied. Both these terms represent the exchange of water vapour from the atmosphere with the surface and this is governed by the flux of latent heat (L_s). This can be calculated using an energy balance equation which states that the surface heat flux (G_s) is determined by the net sum of the energy fluxes:

$$G_s = R_{long-net,s} + R_{short-net,s} - H_s - L_s \quad (10)$$

Incoming short wave radiation is either measured or prescribed in the model and the net shortwave radiation ($R_{short-net,s}$) is calculated using an assumed albedo. The net longwave radiation ($R_{long-net,s}$) is calculated based on parameterisations that include cloud cover, humidity and temperature. The turbulent fluxes for sensible (H_s) and latent (L_s) heat are calculated using bulk exchange equations, and the surface temperature is prognostically determined using a surface slab temperature model. From these equations, and a parameterisation for the surface humidity, the latent heat can be determined.

The resulting surface moisture content (g_{road}) is then used to derive the moisture retention factor ($f_{q,road}$), which is applied to inhibit suspension of accumulated dust (Equations 4 and 5). The moisture retention factor is a simple linear function dependent on a threshold value ($g_{retention-thresh}$) above which full retention is achieved (~ 0.1 mm), Equation 11. A value of $f_{q,road} = 1$ indicates no retention.

$$\begin{aligned} f_{q,road} &= 1 - \frac{g_{road}}{g_{retention-thresh}} && \text{for} \quad g_{road} < g_{retention-thresh} \\ &= 0 && \text{for} \quad g_{road} > g_{retention-thresh} \end{aligned} \quad (11)$$

The surface moisture mass balance and its related production and sink terms are used in the road dust sub-model to determine the surface retention factors ($f_{q,road}$), the dust mass sink due to drainage ($S_{drainage}$), the dust mass sink due to spraying (S_{spray}), the salt concentrations on the road surface and the reduction of wear due to ice on the road surface. In addition to these processes salting does not only contribute to additional mass on the road surface but will also have an impact on the hygroscopic properties of the surface moisture, altering the surface vapour pressure and melt temperature. This process is also to be included in the model and will enable the impact of salting activities, for de-icing or dust binding, to be modelled.

TWO EXAMPLE APPLICATIONS

The emission model has been tested and applied on datasets from both Oslo and Stockholm. In both cases we present the observed and modelled net concentrations, i.e. with the urban background levels removed. The modelled PM concentrations are derived from the model emissions using the observed NO_X concentrations and the estimated NO_X emission rates. This method for converting emissions to concentrations is considered to be more certain than the use of a dispersion model.

In Figure 2 the model has been applied to a major road in Oslo (RV4) where suitable observational data were available for comparison. In this case salting was included in the model as this is carried out frequently in Oslo and has been observed to make up around 30% of the total suspended particles during this period (Hagen et al., 2005). In the first month of observations the observed and modelled concentrations are low, indicating the model correctly predicts retention of the dust load.

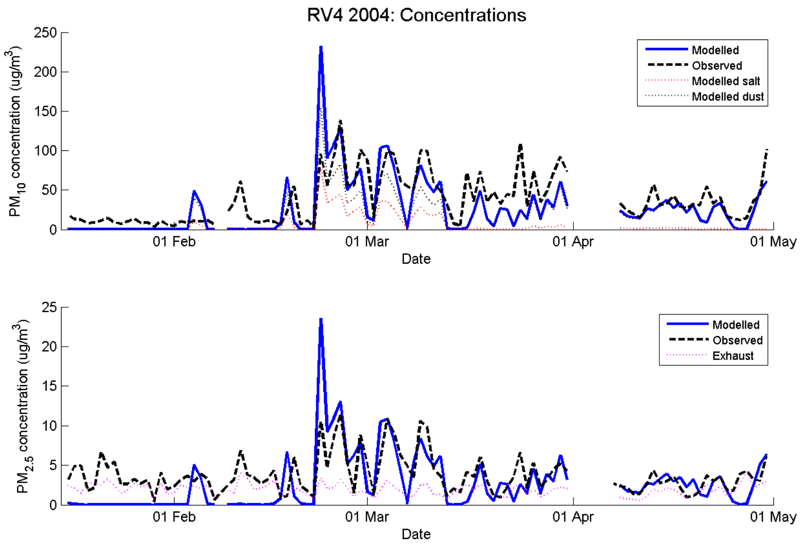

Figure 2. Predicted daily mean PM_{10} (top) and $PM_{2.5}$ (bottom) concentrations for the Oslo example (RV4). Salt is included in the calculations, its rate of application is not known but assumed based on salting rules employed in the city of Oslo. The modelled PM (blue line) is the sum of dust and salt suspension (no exhaust). Also included in the $PM_{2.5}$ plot are the calculated concentrations from exhaust emissions only.

In Figure 3 an example application for the period 2008-2009 in Hornsgatan, Stockholm is shown. No salting is included in this case. At this site road moisture measurements were available and these have been used (Figure 3 bottom) to determine the surface retention instead of using the surface moisture model (Figure 3 top). There is significant improvement when the observed moisture is used, indicating the importance of accurately predicting this parameter. Further results of the model application in Stockholm can be found in (Johansson et al., 2011).

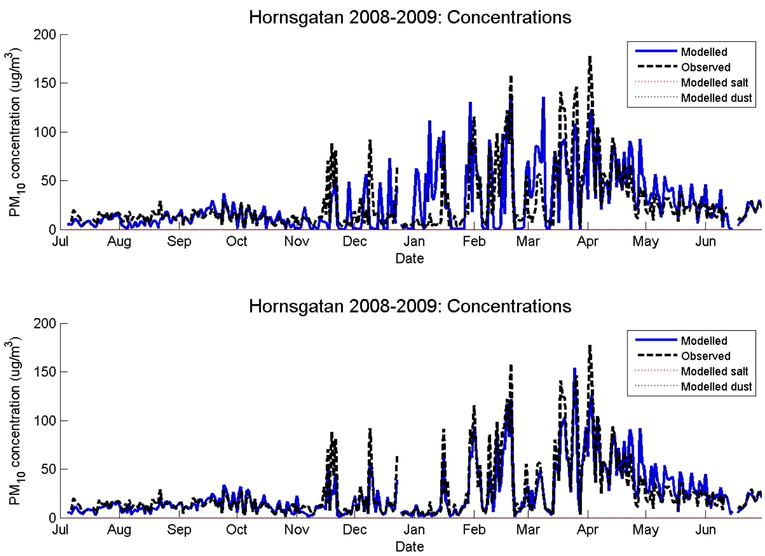

Figure 3. Predicted daily mean PM_{10} concentrations in Hornsgatan in Stockholm. Top plot shows the model results using the surface moisture model. The bottom plot shows the results when using the observed surface moisture to determine road dust retention. Salt is not included in the calculations (‘Modelled salt’ = 0) and as a result the ‘Modelled’ concentrations are equivalent to the ‘Modelled dust’ concentrations. Exhaust is not included in these results.

CONCLUSIONS AND FUTURE DIRECTIONS

This paper provides a short overview of the modelling concept behind the road dust emission model GRD-2 and progress so far with the model. A number of important processes are described in the model and it has been successfully tested on both Stockholm and Oslo data sets. Though the model is already well developed there are still a number of open questions and further developments that need to be addressed. Further developments include:

- The change in hygroscopic properties (surface vapour pressure and melt temperature) of the road surface, with the introduction of salt and dust binding measures, will be implemented in the model.
- The shoulder component of the model has not shown any significant impact on the emissions and it will likely be excluded from further model development.
- There is a need to differentiate between size fractions of the dust loading, particularly when sanding is applied. It is intended to redefine the model so that it includes 'sand' and 'dust' size fractions. This will allow an improved description of the impact of sanding as well as a more physically based description of road wear through abrasion (sand paper effect).
- The vehicle speed dependence on the road wear will be improved based on experimental data.
- The model will be applied to a number of non-Nordic countries to assess its applicability in other environments.
- A direct comparison of the road surface moisture model with surface moisture measurements will be carried out.
- Improved data concerning road maintenance activities will be included and the model tested against these.

There are also a number of unanswered questions concerning the model:

- To reproduce the summer time emissions of PM_{10} in Stockholm a significantly higher wear rate has been employed in the model than is expected from laboratory studies of summer tyres. There remains an open question as to the source of these emissions, whether current road wear rates for non-studded tyres are poorly reflected or if other sources are responsible.
- The impact of sanding has not been properly tested with the model. Quantification of the emissions from sanding, as well as salt, is an important application of the model for European AQ Directive applications. Improved data is required to assess this.
- A number of the parameters used in the model are currently poorly defined. Further measurements of processes, such as road dust loading, are required for improving these.

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