EVALUATION AND INTER-COMPARISON OF OPEN ROAD LINE SOURCE MODELS CURRENTLY IN USE IN THE NORDIC COUNTRIES

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Abstract
The aim of this study is to inter-compare and evaluate operational open road Gaussian line source models currently in use in the Nordic countries Norway, Denmark and Finland. By comparing the models and their results on different datasets, a more robust and objective assessment of model performance and applicability can be made. Four models, HIWAY2-AQ, OML-Highway, CAR-FMI and WORM, are applied to datasets from three measurement campaigns from each of the mentioned countries. A more specific target is to determine the conditions under which the models perform well or poorly in order to focus attention on these aspects in future model development. The various models are evaluated primarily with regard to wind speed, wind direction and atmospheric stability in order to identify problem areas.
Generally, the correlation between model estimates and observations decreases when normalising with emissions, due to the significant positive correlation between observed concentrations and emissions. Furthermore, we found a reduction of bias when normalising the Norwegian and Danish data, caused by overestimation of the dispersion at lower emission values. This occurs because the initial dispersion is too large in all the models. For higher emissions at the Danish site, the relative bias was higher, compared with the relative bias at the Norwegian site, indicating the influence of traffic density and vehicle speed (which are both largest at the Danish site) on traffic produced turbulence and model performance. OML-Highway, however, performs best in this regard due to its more advanced parameterisation of traffic produced turbulence based on production and decay of turbulent kinetic energy.
With regard to horizontal profiles, *RB* for CAR-FMI increased as function of distance from the road, indicating that the Lagrangian time scales are too short.

***Key words**: Line source; Highway; Gaussian; Traffic produced turbulence; Normalisation; Dispersion*

1. INTRODUCTION

Model inter-comparison studies provide a robust basis for evaluation, development and improvement of models. When several different models are applied to several different datasets, we obtain insight and knowledge on specific differences between the models, and on the parts of the models that perform well or poorly. Gaussian models, however, typically perform poorly under low wind speed conditions, or when the wind direction is close to parallel to the road, as described in Benson (1992). Inter-comparison studies have been performed earlier by e.g. Oettl et al. (2001) and Levitin et al. (2005).

In the current study, we apply a modified version of the HIWAY-2 model called HIWAY2-AQ, the Danish OML-Highway model, the Finnish CAR-FMI model and the new Norwegian WORM model, to three different datasets in the Nordic countries. The study addresses only roadside environments in open and rural sites. The inter-comparison is aimed at analysing the variability and quality of these various open road line source (ORLS) models.

Section 2 contains a description of the models and methodology, the results are given in section 3 and some main conclusions are given in section 4.

2. MODEL DESCRIPTIONS AND METHODOLOGY

The four models are applied to data from measurement campaigns in Norway, Denmark and Finland, containing air quality and meteorological measurements carried out near major roads/highways. Most of the campaigns include a number of stations placed at different distances from the road. For this particular study, however, one station at each site situated approximately 50 m from the road is used for the inter-comparison. The pollutant NO_x ($NO+NO_2$) is considered, since this compound was measured at all sites, its emissions are best known and it can be treated as a tracer for the short time scales involved.

Each model calculates concentrations at various receptor points by integrating concentrations from a set of infinitesimal point sources defined along each line source using the Gaussian plume equation as a basis (Seinfeld et al., 1998):

$$C = \frac{Q}{u_h}\int_0^D \frac{1}{2\pi\sigma_y\sigma_z}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left[\exp\left(-\frac{(z-h)^2}{2\sigma_z^2}\right)+\exp\left(-\frac{(z+h)^2}{2\sigma_z^2}\right)\right]dl \qquad (1)$$

where C is the concentration at the receptor point, Q is the line source emission strength (assumed constant along the line source), u_h is the effective transport velocity, D is the length of the line source, σ_y and σ_z are the Gaussian horizontal and vertical dispersion parameters, respectively, h is the effective source height and ℓ is the line source.

The above formulation does not include internal reflections from the top of the boundary layer. Extra terms are included in some of the models to account for this.

A common assumption in all the models is that the total Gaussian dispersion parameter, $\sigma_{y,z}$, can be represented as a combination of atmospheric turbulence, $\sigma_{ya,za}$, and traffic produced turbulence (TPT), $\sigma_{y0,z0}$:

$$\sigma_{y,z}^2 = \sigma_{ya,za}^2 + \sigma_{y0,z0}^2 \qquad (2)$$

All models except OML-Highway base their formulation of TPT on the formulation in the HIWAY-2 model (Petersen, 1980), which is a semi-empirical treatment based on the General Motors experiments (Cadle et al., 1976):

$$\sigma_{z0} = 3.57 - 0.53U_c \qquad (3)$$

$$\sigma_{y0} = 2\sigma_{z0} \qquad (4)$$

where U_c is the aerodynamic drag. TPT in OML-Highway is based on a parameterisation of the decay of turbulent kinetic energy:

$$\sigma_0(t) = \sigma_{initial} + u_{TPT}\,\tau\left(1 - \exp\left(-\frac{t}{\tau}\right)\right) \qquad (5)$$

where $u_{TPT} = \sqrt{e}$. $\sigma_{initial}$ is the initial dispersion, τ is the time scale for the decay of TPT and e is turbulent kinetic energy.

Table 1 below summarizes some other features and differences between the models, of significance for the results.

Table 1. Main features and differences between the models.

Institute	NILU	NERI	FMI	NILU
Model	HIWAY2-AQ	OML-Highway	CAR-FMI	WORM
Model type	All models: Slender plume Gaussian steady state			
T_L^e	-	Implicit, dependent on met. conditions	Unstable, L^f<0: T_L=300 sec. Stable, L>0: T_L=30 sec	T_L=300 sec
Integration method	Numerical, Richardson extrapolation	Analytical for crosswind direction, numerical for along wind direction	Analytical (Luhar and Patil, 1989)	Numerical, Gaussian quadrature
TPT	Semi-empirical, Eq. 3-4	Empirical, Eq. 5	Semi-empirical, based on Eq. 3-4	Semi-empirical, Eq. 3-4

[a]Minimum wind speed, [b]Convective velocity scale, [c]Mixing height, [d]Friction velocity, [e]Lagrangian time scale, [f]Monin-Obukhov length.

The overall model performance on all data is assessed using the Pearson coefficient of determination (denoted by R^2) and relative bias (denoted by RB), where $RB=(C_{pred}-C_{obs})/C_{obs}$. Furthermore, we focus on normalised concentrations, i.e. the observed and model calculated concentrations are divided with emissions Q (Q-normalisation).

3. RESULTS AND DISCUSSION

Q-normalising the concentrations

Table 2 presents the model results for all models applied to all data in terms of R^2. Both the non-normalised and Q-normalised results are presented for comparison. The main feature is a decrease of R^2 when normalising the data, due to the natural positive correlation between observations and emissions. Generally, when Q-normalising the concentrations, the larger the decrease in R^2, in respect to the non-normalised values, then the less the dispersion parameters are related to the observations.

Figure 1 presents RB for all models applied to the Danish data. The values of RB for the models applied to the Finnish data are similar for both non-normalised and Q-normalised concentrations (not shown). However, in the Danish dataset, and also to a lesser extent the Norwegian dataset (not shown), RB of the Q-normalised concentrations is less than RB of the non-normalised concentrations. This occurs because the models underestimate the observed concentrations when the traffic volumes, and hence the emissions, are low. Assuming the emissions are still valid, this indicates that all the models overestimate the dispersion at lower traffic volumes and this in turn is related to the initial dispersion by TPT, which appears to be too large for low traffic volumes. This effect is not obvious when absolute concentrations are used since these are dominated by high traffic volume cases.

Furthermore, analysis shows that all models except OML-Highway overestimate more for high emission values when applied to the Danish data than when applied to the Norwegian data (not shown here). The Danish measurements were carried out on a much more trafficked highway than the Norwegian, approximately 100 000 vehicles/day compared to approximately 36 000 vehicles/day, respectively. The average vehicle speed at the Danish site was also higher, ~109 kmh^{-1} compared to ~90 kmh^{-1} at the Norwegian site. As a result, dilution due to TPT should be higher at this site. OML-Highway performs better for higher emissions due to its formulation of TPT, based on a parameterisation of the decay of turbulent kinetic energy.

Table 2. Coefficient of determination, R^2 for all models applied to all data, for both non-normalised and *Q*-normalised results.

	HIWAY2-AQ		OML-Highway		CAR-FMI		WORM	
Nor. data	Non-norm.	*Q*–norm.	Non-norm.	*Q*–norm.	Non-norm.	*Q*- norm.	Non-norm.	*Q*–norm.
St. 1	0.50	0.18	0.72	0.69	0.50	0.23	0.72	0.42
St. 2	0.52	0.21	0.68	0.60	0.46	0.28	0.68	0.47
St. 3	0.48	0.20	0.62	0.53	0.46	0.37	0.64	0.49
Dan. data								
St. 1	0.38	0.18	0.75	0.65	0.49	0.25	0.65	0.28
St. 2	0.34	0.24	0.74	0.61	0.41	0.36	0.70	0.36
St. 3	0.31	0.27	0.71	0.56	0.43	0.50	0.71	0.43
Fin. Data								
Van#1	0.51	0.49	-	-	0.47	0.44	0.51	0.51

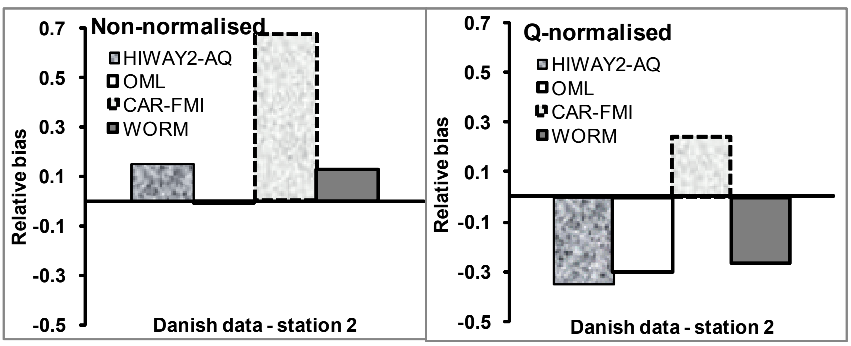

Figure 1. Relative bias (*RB*) for all models applied to the Danish data. Left: non-normalised results, right: *Q*-normalised results.

The effect of wind speed and wind direction

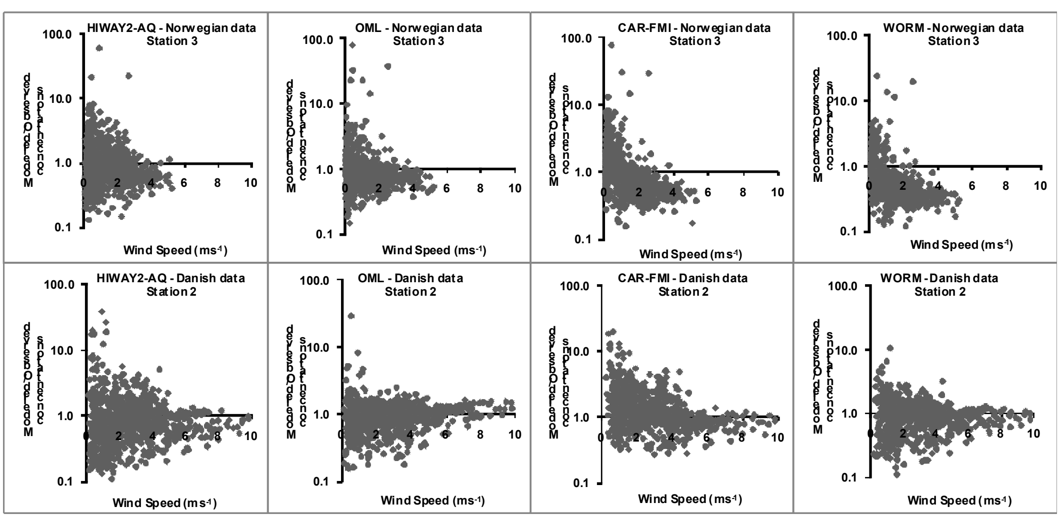

Figure 2. Scatter plots of the ratio modelled/observed concentrations versus wind speed at 2 m above ground for all models applied to the Norwegian (above, station 3) and Danish (below, station 2) data.

Figure 2 presents scatter plots of the ratio of modelled to observed concentrations versus wind speed at 2 m above ground for all models applied to the Norwegian and Danish data at station 3 and 2, respectively. In general, more scatter and over-predictions are present for low wind speed conditions, due to more uncertainty in the modelling and a stochastic part to the observations, which will lead to scatter irrespective of the quality of the modelling. For the Norwegian data at higher wind speeds, underestimations are evident, more so than on the Danish site. This difference occurs as a result of higher traffic volumes and traffic speed at the Danish site, compared to the Norwegian site, as previously mentioned.

Horizontal profiles

In order to study how the models perform with regard to distance from the road, *Q*-normalised *RB* is shown in fig. 3 for each station at the Norwegian and Danish sites. The behaviour of *RB* is dependent on both the initial dispersion, caused by TPT, and the atmospheric dispersion. When applied to both datasets, *RB* for CAR-FMI increases with increasing distance from the road, indicating that the dispersion does not evolve at the rate indicated by the observations. The Lagrangian time scales, T_L, are probably too small in this model (see table 1). With regard to all models except CAR-FMI the values of *RB* decrease as a function of distance from the source. The average observed wind speed at the Danish site is higher than at the Norwegian site. Hence, the atmospheric turbulence plays a more significant role as the significance of TPT decreases with distance from the source.

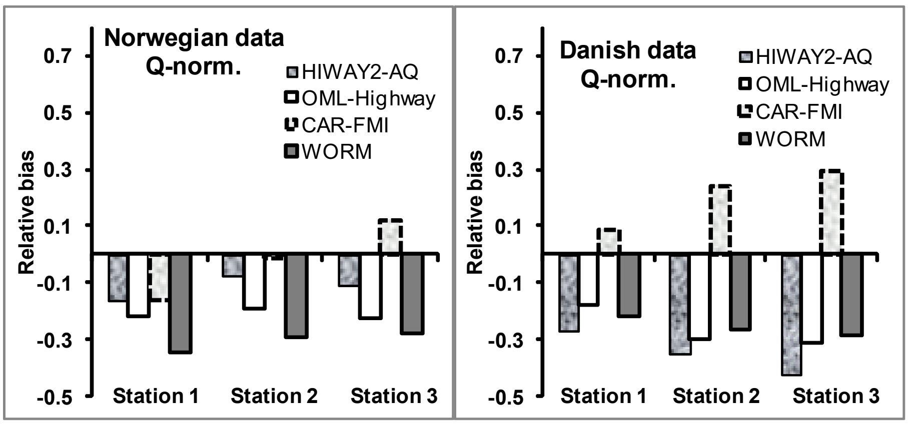

Figure 3. *Q*-normalised relative bias (*RB*) for all models applied to the Norwegian data (left, all stations) and Danish data (right, all stations).

4. CONCLUSIONS

Four models have been compared and evaluated based on their application on datasets from measurement campaigns in Norway, Denmark and Finland. The specific aim was to determine under which conditions the models perform well or poorly. The measurement campaigns were conducted near highways in open environments.

When normalising with emissions, R^2 generally decreased as the natural positive correlation between emissions and observations is removed. Analysis of the data indicated that reduction in *RB* in the Norwegian and Danish data after normalising was caused by overestimation of the dispersion at lower traffic volumes and lower emission values. This occurred because the initial dispersion, is too large in all the models. Also, all models except OML-Highway gave higher *RB* for high emission values when applied to the Danish data than when applied to the Norwegian data, due to the increased significance of TPT at the more heavily trafficked Danish site. The latter feature was also seen in the scatter plots of the ratio of modelled to observed concentrations versus wind speed, at higher wind speeds. OML-Highway performed best in this regard due to its parameterisation of TPT based on decay of turbulent kinetic energy.

OML-Highway's parameterisation of TPT (or similar ones), should be implemented in ORLS models, to describe the turbulence produced by the traffic. However, the initial dispersion must be reduced in order to describe the concentrations when the emissions are low. The OML-Highway formulation is currently being implemented in WORM. Furthermore, in order to reduce uncertainties appearing under near to parallel wind directions, Gaussian quadrature methods, or other highly accurate numerical integration methods, should be implemented in ORLS models.

With regard to horizontal profiles, *RB* for CAR-FMI increased with increasing distance from the road. This indicates that the Lagrangian time scales, T_L, are too short, and need to be revised.

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