NEMO – A UNIVERSAL AND FLEXIBLE MODEL FOR ASSESSMENT OF EMISSIONS ON ROAD NETWORKS

Authors: Martin Dippold, Martin Rexeis, Stefan Hausberger*

Institute for Internal Combustion Engines and Thermodynamics, Research Area Emissions, Graz University of Technology (TUG), 8010 Graz, Austria

INTRODUCTION

Today typical application fields of emission models cover the depiction of complex measures like environmental zones or promotion of alternative propulsion systems. Often air quality modelling is linked to the emission simulation which results in a high demand on the spatial resolution of the model results. For these challenging application fields the model NEMO (Network Emission Model) was developed at TUG.

NEMO combines both, a detailed simulation of the fleet composition and of emission factors (emissions in grams per kilometre) on a vehicle segment level. All relevant model parameters can be changed by the user to provide a maximum range of application fields. For standard calculations - which are based on a standard scenario for fleet composition and emission behaviour - a default parameterisation is available to enable a user friendly model application, where only the street network has to be provided as model input.

A crucial point in emission modelling is the characterisation of driving conditions on the single road sections. For this task the two most common methods are:

I. If the Handbook Emission Factors of Road Transport (HBEFA, 2010) is used, so called “traffic situations” (TS) have to be allocated to the street sections. In total 276 traffic situations are defined which are characterised by criteria like the street type or classes for traffic density. For each TS emission factors are available in the HBEFA, which have been simulated by a detailed micro-scale emission model (“PHEM” e.g. (Zallinger, 2010), (Hausberger, 2009) and (Rexeis, 2009)).

II. Other models, such as COPERT 4 use the parameters “average speed” and road gradient to characterise the driving conditions. Emission factors are then depicted by simplified functions derived by best-fit curves for the set of HBEFA emission factors or other sources of emission data (e.g. chassis dyno measurements) over average cycle speed and for certain road gradients.

Both methods have well known disadvantages. The HBEFA method of discrete allocation of TS to road sections is based on rather vague definitions and can hardly be fully automatized for large scale road networks. The average speed approach has the main disadvantage of simplified depiction of emission behaviour. Additionally a founded method of assessment of average speed for the different road section is needed.

With NEMO a new method of assessment of emissions on road networks was developed. The approach allows for basic simulation of emission factors for all types of vehicles and all kind of driving behaviour without requiring the huge amount of time-resolved input data of micro-scale models. Additionally a method is proposed how the parameterisation of the single road sections in terms of driving behaviour can be accomplished in a robust and automatized way by a link to traffic models like VISUM.

SIMUATION OF FLEET COMPOSITION

In the emission simulation the vehicle fleet is divided into groups with similar emission behaviour, the so called “vehicle segments”. The differentiation criteria available for the NEMO vehicle segmentation are:

1. Vehicle category (e.g. passenger cars, light duty vehicles, rigid trucks …)
2. Propulsion concept (e.g. Otto engine, Diesel engine, electric vehicles …)
3. Size-class (e.g. differentiated according to maximum allowed gross weight)
4. Technology-class (e.g. Euro-class or combination of Euro-Class with emission reduction technology (EGR, SCR))
5. Additional retrofit exhaust gas aftertreatment-systems (e.g. diesel particulate catalysts)
6. Fuel types which are used within each propulsion concepts

The last mentioned differentiation criteria allows to depict the effect e.g. of Otto engine driven vehicles with a mix of different gasoline fuels (e.g. E5, E10 and E85) on emissions and amount of consumed fuels.

For the overall emission output the shares of the different vehicle segments on the overall mileage are relevant. NEMO comprises a fleet module which calculates the vehicle stock and the mileage distribution according to the vehicle segments in a pre-processing step before start of emission simulation. Details on the NEMO fleet module can be found in (Rexeis, 2005) or (Hausberger, 1997).

The data for the Austrian “standard” traffic scenario is available in the basic set up of the model. The user simply has to supply the average daily traffic volume and the road category for the considered street sections. If the shares of particular vehicle categories on the total traffic volume are given from traffic survey or prognosis, they also can be used as optional model input, the model then only calculates the composition inside each vehicle category according to the subordinate vehicle layers.

SIMULATION OF EMISSION FACTORS

Instantaneous emission models like PHEM calculate emissions on a second by second basis, which requires input on driving conditions as a time series (vehicle speed and road gradient, optional gear or engine speed) and very detailed information on engine and vehicle specifications (engine maps for each emission component, dynamic correction functions, gear ratios …). For an emission model, which focuses not on single vehicles in precisely defined driving situations but on the assessment of fleet emissions in a road network, a more aggregated approach is assessed to be appropriate because:

- the complexity of an instantaneous emission model and the amount of required input data for a detailed simulation for all vehicles in each segments of the fleet would make the calculation of the emissions in a road network hardly operable (e.g. the user would have to provide driving cycles on a second by second basis for each vehicle category in each road section)
- the loss of accuracy from the simulation side when changing to a more aggregated model approach is much smaller than the inaccuracy which arises from uncertainties linked to the composition of the fleet and the presumed average driving behaviour

Of course a suitable emission model even with an “aggregated” approach still has to guarantee correct assessment of basic influences of driving behaviour, vehicle specifications and exhaust gas aftertreatment systems.

In NEMO the basic principle for the simulation of the vehicle emissions is the strong correlation of the engine specific emission behaviour (emissions in grams per kilowatt-hour engine work) with the cycle average engine power in a normalised format, which was found to be valid for all engines inside a certain vehicle category, propulsion concept and emission standard.

In a first step NEMO calculates the cycle average normalised engine power based on the vehicle specifications, cycle average kinematic parameters (average velocity, share of standstill and the average mechanical brake deceleration which specify the driving behaviour) and the road gradient. The normalisation of the cycle average engine power is done by division by the engine rated power. Figure 1 exemplarily compares the results for cycle average normalised engine power for the set of HBEFA 3.1 cycles calculated with PHEM and with NEMO for a EURO 4 passenger car. Although only three cycle average parameters are used in NEMO, the correlation with the detailed simulation in PHEM can be considered very good, small deviations mainly occur for cycles with very low average engine loads (especially for cycles with slow average speeds and high shares of standstill).

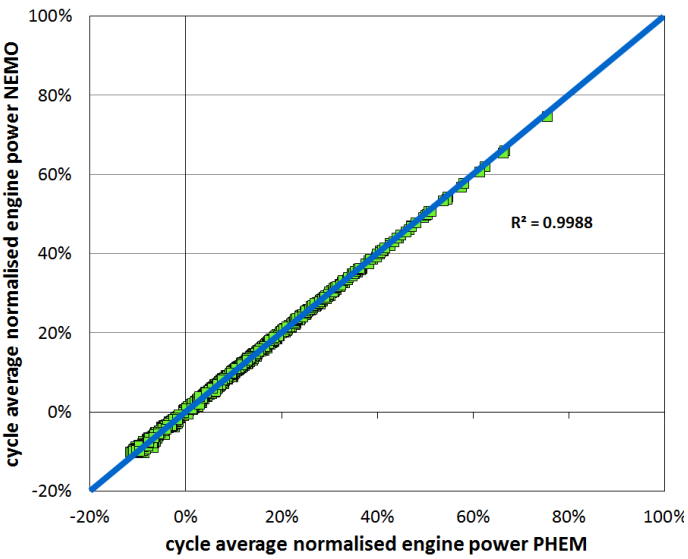

Figure 1: Comparison of the cycle average normalised engine power calculated from second by second data (with PHEM) and based on cycle average kinematic parameters (NEMO)

The specific emission behaviour is depicted in NEMO by characteristic curves as a function of cycle average normalised engine power for each combination of vehicle category, propulsion concept and technology-class. These curves are parameterised based on the entire set of emission factors for the HBEFA3.1 driving cycles simulated with PHEM. For the purpose of NEMO parameterisation a semi-automatic interface between PHEM and NEMO was developed, which allows for quick adjustment of the NEMO data status to the latest PHEM version.

The engine specific emission behaviour is defined according to equation (1a) for cycles with an average normalised engine power greater equal 0.5% and smaller equal - 0.5. As an example the characteristic curve for specific NOx emission behaviour of EURO 4 Diesel passenger cars is shown in Figure 2 (left picture).

Driving cycles with road gradients of –2% and lower can result in a cycle average normalised engine power near or even below zero (motoring). Cycles with an average normalised engine power near to zero are dealt with a different approach in order to avoid a division by zero. Here the “engine specific emission behaviour” is calculated according to equitation (1b). For these cycles a good correlation of specific emission behaviour with the average cycle speeds can be found (see Figure 2, right picture).

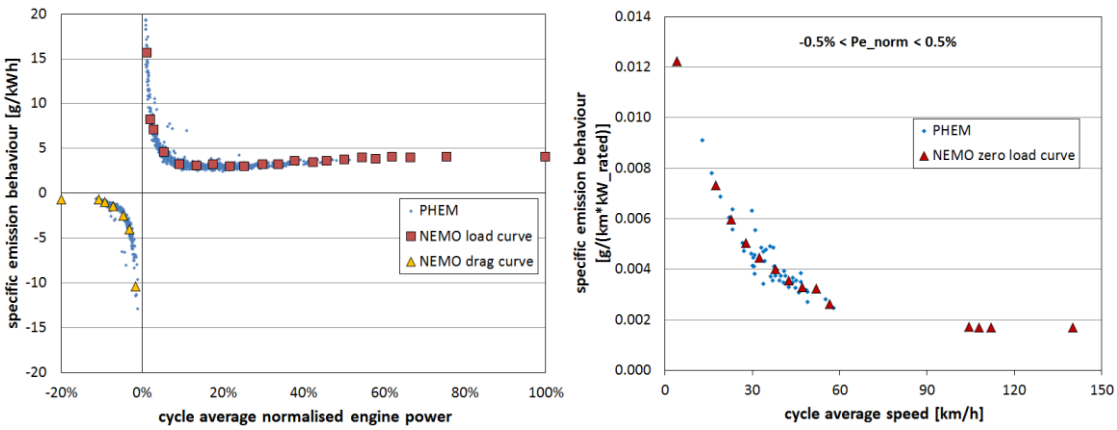

Figure 2: Example of parameterization of NEMO engine specific emission functions based on PHEM emission factors (NOx emissions of EURO 4 Diesel passenger cars)

$$E_{spec} = E \cdot \frac{v_{av}}{P_{rated} \cdot P_{norm,av}} \qquad \text{...for } |P_{norm,av}| \geq 0.5\% \qquad (1a)$$

$$E^{*}{}_{spec} = \frac{\mathrm{E}}{P_{rated}} \qquad \text{...for } |P_{norm,av}| < 0.5\% \qquad (1b)$$

with:

E	……	emission factor [g/km]
E_{spec}	……	specific emission level [g/kWh]
E^*_{spec}	……	specific emission level in average zero load conditions [g/(km*kW$_{rated}$)]
P_{rated}	……	rated engine power [kW]
$P_{norm,av}$	……	cycle average normalised engine power [%]
v_{av}	……	cycle average vehicle speed [km/h]

The NEMO emission factors then are calculated by inversion of equation (1a) and (1b). If a combination of vehicle speed and road gradient has been specified in the road network, which cannot be followed by the vehicle because of lack of engine power, NEMO automatically reduces the vehicle speed and the dynamics of the driving cycles in order to ascertain a realistic vehicle speed for the calculation of the emission factors.

A comparison of emission factors simulated with the detailed emission model PHEM and determined with the simplified NEMO approach is given in Figure 3 on example of NO_x for EURO 4 diesel passenger cars. The NEMO results come quite close to the PHEM values for nearly all kinds of driving behaviour and road gradients. Larger deviations mainly occur for cycles with a high share of standstill. However, especially for those kinds of driving conditions (e.g. urban stop and go driving) the uncertainty resulting from the representativeness of the used driving pattern (in terms of to average velocity, time share of standstill, driving dynamics) is assessed to have at least similar impact on the emission results than the uncertainty of the emission modelling. For heavy duty vehicles the NEMO approach provides an even better prediction quality as the emission levels correlate better with the average engine power demand and are less effected by specific engine map characteristics and gear shift behaviour (which can only be depicted by the PHEM approach).

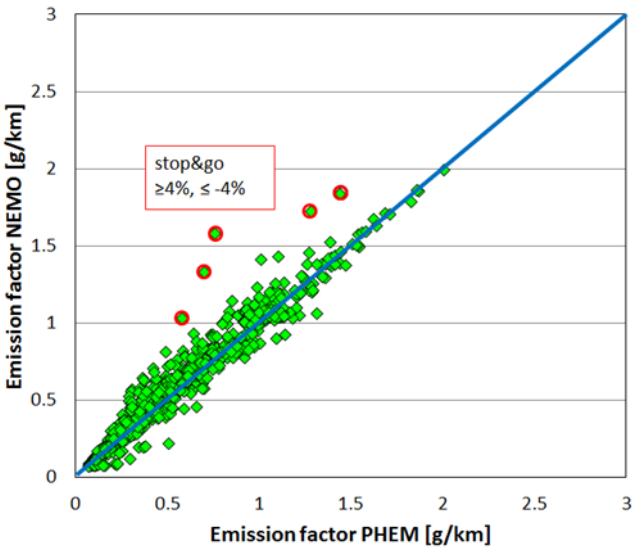

Figure 3: Comparison of emission factors simulated with PHEM and NEMO for the entire set of HBEFA3.1 driving cycles on example of NO_x of EURO 4 Diesel passenger cars

This approach is applied in NEMO for all regulated pollutants (NO_x, THC, CO, PM exhaust) for hot vehicle operation. Fuel consumption is simulated based on a slightly extended method which also considers the energy content of the applied fuel type. The emissions of CO_2 and SO_2 are simulated based on fuel consumption and fuel specifications. The non-regulated pollutants N_2O, NH_3 CH_4, NMHC and C_6H_6 are calculated with an approach similar to the HBEFA 3.1 based on fixed emission factors for certain vehicle categories and driving situations.

Additional influencing mechanisms on the emission output of road traffic implemented in NEMO are:

- Cold start effects (data and approach compatible to the HBEFA3.1)
- Influence of mileage and maintenance on the emissions of gasoline vehicles (Samaras, 2004)

- Calibration of fuel consumption based on statistics of g/km CO_2 of new registered vehicles in the NEDC type approval and literature on the discrepancies between NEDC and real world CO2 reduction rates (Mock, 2012)
- Evaporation from gasoline emissions (data and approach compatible to the HBEFA3.1)

Particle emissions due to vehicle induced abrasion and re-suspension processes ("PM non-exhaust") are taken into account by NEMO in addition to the PM-exhaust emissions. Default datasets available in NEMO contain the values published in (Düring, 2004) and (Schmidt, 2011): The user is of course free to import customised PM non-exhaust emission factors.

"ADVANCED LINK" OF TRAFFIC MODELS WITH NEMO EMISSION SIMULATION

The characterisation of driving conditions is a crucial parameter in the assessment of emissions of road transport. Especially if the calculated emissions are used for air quality modelling a high requirement for correct allocation of local driving conditions to all road sections is essential.

Traffic models are used in nearly all applications of emission assessment for road networks in order to provide the distribution of traffic volumes on the network. Such traffic models use the travel time as resistance parameter for the assignment of traffic volumes to the different road sections. Several models additionally include node or turn impedances to depict the delay time at crossings. This coherence of kinematic model parameters with the NEMO approach for emission simulation as described above offers the possibility to directly link emission simulation with traffic modelling. Such a method provides an objective and automated characterisation of driving conditions if the boundary conditions that the traffic model is well parameterised and the transfer of parameters between traffic and emission model is made methodically correct are met.

Such an "advanced link" of NEMO with traffic modelling was developed in a project funded by the Austrian FFG ("ROdEM", (Kriebernegg, 2010)) using the traffic model VISUM from PTV AG. This link between NEMO and VISUM was done for two setups of the traffic model for the road network under consideration:

1. The "daily average method", where the assignment of traffic volumes was based on the traffic volumes in the peak hour. In this approach the crucial point is that the emission model is fed with the correct "traffic volume weighted average daily velocity" but not the average velocity for the peak hour. Such a conversion of velocities can be done based on the traffic model parameters in the capacity-restraint-functions and the daily variation curves for traffic volumes.
2. The "hourly based method", where the assignment of traffic volumes is separately done for each hour. In this approach also the emission model was run with 24 different values of traffic volumes and average speeds for each road section.

The daily average method (1.) is the most frequent applied method in the common use of traffic models. The comparison of emission results between (1.) and (2.) showed that on road sections with high traffic loads the daily average method leads to a slight underestimation of emissions (e.g. -2% for CO2, -5% for NOx, -20% for HC for a main street in the inner Graz area) compared to the hourly based method due to the underestimation of emissions in stop and go conditions. However this relatively small difference - compared to the total uncertainties in the chain of traffic and emission modelling - is interpreted in a way that from point of emission modelling there is usually no absolute necessity to choose the much more complex method of parameterising a traffic model on an hourly basis. Certainly, in applications where e.g. effects of reducing stop-and-go conditions are addressed, an hourly simulation can be advantageous.

Independent of the chosen method the determination of realistic average speeds on the road section in conditions of free traffic flow is essential. For this purpose in the ROdEM project the travel time for a certain sample of the street sections has been determined by test drives. The kinematic parameters (share of standstill, average mechanic brake deceleration) have then been calculated in NEMO internally based on characteristic curves as a function of average speed, road type (urban, rural or motorway) and road gradient. If the VISUM parameter "node impedance" can be applied to assess the share of standstill in a general valid way will be subject of further investigation.

Whether this "advanced link" of traffic modelling with emission simulation can be applied to all kinds of traffic models and traffic model parameterisations shall be subject of further research. In any case it was concluded that future development of emission models as well as traffic

models should also pay some focus to consider features and problem fields of adjacent modelling disciplines.

LINK OF EMISSION SIMULATION WITH AIR QUALITY MODELLING

In the majority of NEMO applications the emission results are directly used as input for air quality assessment. For this task the dispersion model system GRAL was developed at the Institute especially for micro scale – meso scale applications in complex terrain. This model system consists mainly of two modules, the non-hydrostatic prognostic wind field model GRAMM (Almbauer et al., 2000 and Öttl, 2000) and the Lagrange particle model GRAL (Öttl et al. 2012). GRAL was especially developed for environmental assessment studies on local scale in complex terrain but in general it can handle any application from small scale urban canyons to large scale air quality inventories. GRAL and NEMO have been integrated into a common Graphical User Interface which allows for efficient handling of various model input data (e.g. meteorological data, NEMO related data, data on other emission sources) on a GIS basis. Figure 4 illustrates the chain of results ranging from the traffic model, NEMO emission output and finally GRAL NO_x concentration levels for the investigation area Klagenfurt (population: ~90 000).

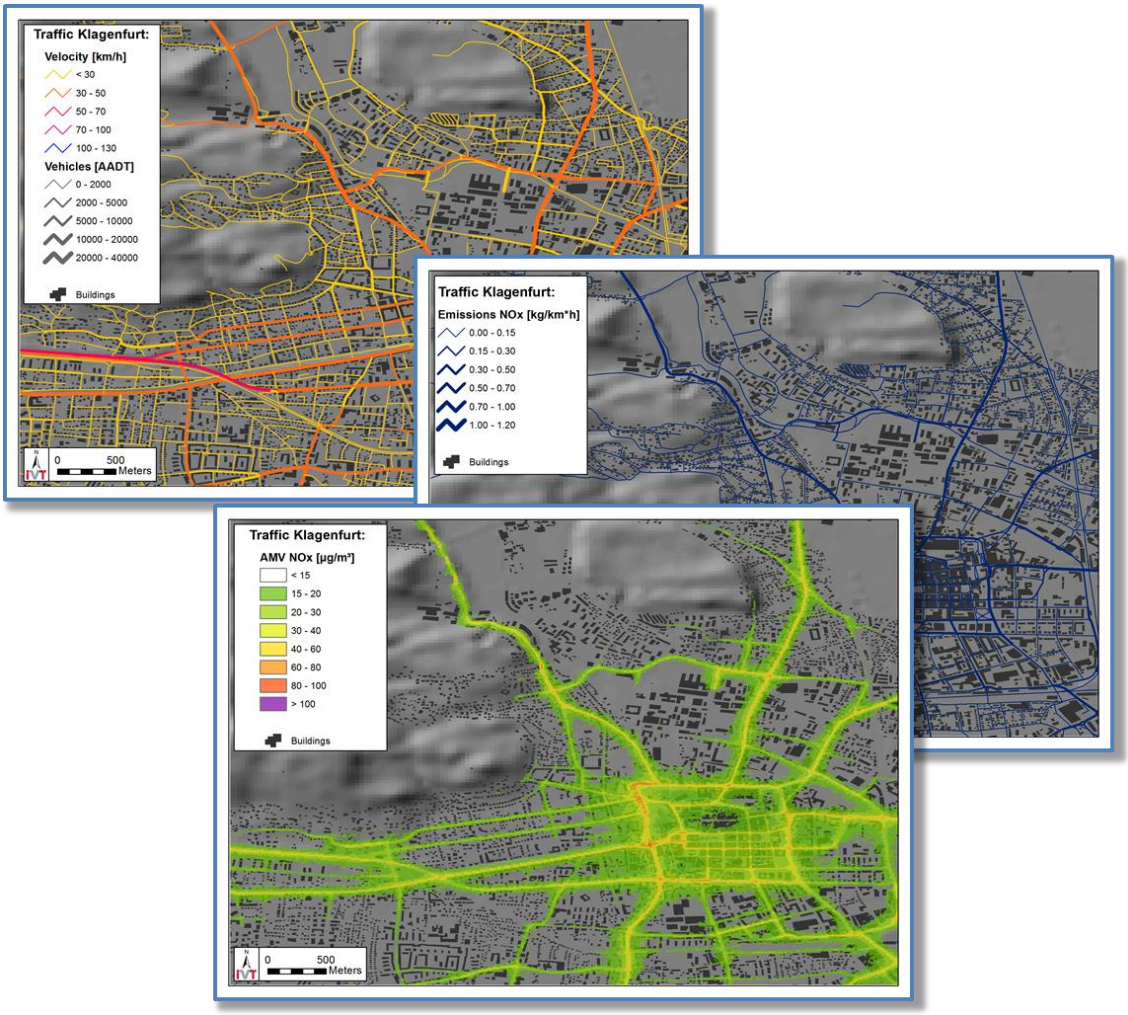

Figure 3: Full model chain of results from traffic model, NEMO and dispersion model GRAL on example of the air quality inventory for the City of Klagenfurt (AADT = annual average daily traffic, AMW = annual mean value)

OUTLOOK

NEMO will be applied for calculation of Austrian fleet composition for the upcoming update of the HBEFA (Version 3.2). By then, the latest emission data available in PHEM for simulation of

HBEFA3.2 emission factors will also be transferred into the NEMO model. From the year 2013 on it is planned to use NEMO also for the National Austrian Air Pollutant Inventory.

Further methodical research will focus on the modelling of alternative propulsion concepts (e.g. hybrid electric vehicles) and on a systematisation of the parameterisation of driving conditions based on a deeper understanding of traffic models and real world conditions.

SUMMARY

The model “NEMO” (Network Emission Model) was especially being developed for the calculation of emissions on road networks. It combines a detailed simulation of fleet composition and of vehicle emission factors. Compared to micro-scale emission models - which are based on a time-resolved simulation approach – it uses an emission factor simulation method based on driving cycle average kinematic parameters, vehicle specifications and characteristic curves for specific emission behaviour for each propulsion technology. Despite the cycle average approach NEMO provides a good model accuracy for all vehicle categories and all types of vehicle operation. All known influencing mechanisms on emission output of road transport (e.g. cold start, mileage influence, evaporation...) are covered in the model.

In this paper a method is proposed which allows for an objective and automated characterisation of driving behaviour on the different sections of a road network based on an “advanced link” of NEMO with the traffic model VISUM. This method is based on the conversion of the traffic model parameter “peak hour travel time” into the emission model parameter “traffic volume weighted average daily velocity”. A comparison of integrated VISUM-NEMO results based on daily average parameters with an hourly based model setup showed only small differences in simulated emissions even for road sections with high traffic volumes.

NEMO also offers the option of direct link of emission modelling with the dispersion model system GRAL. So NEMO can provide a straight forward solution to close the gap between traffic modelling and air quality assessment.

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