Master Thesis
Analysis and Modeling of Real Driving Emissions (RDE)

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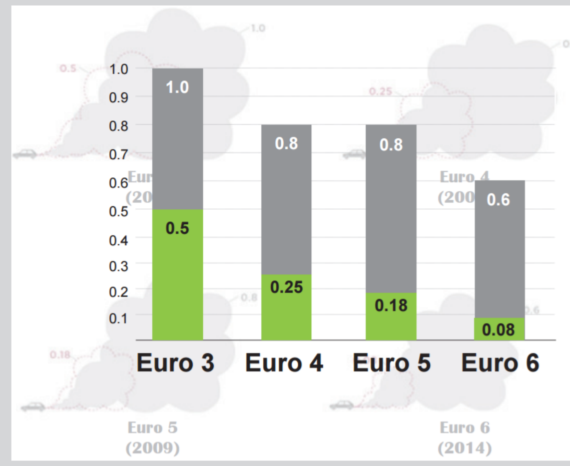
Abstract

Real driving emissions (RDE) are gaining attention due to the deviation of legal limitations and combustion engine vehicles' exhaust pipe emissions. The state-of-the-art approach for pollutants assessment involves test bench measurements for representative driving cycles and a transfer of obtained emission data to real cars. The transferability of test bench measurements is questionable and hence examined by comparing them with RDE data.
Against this background, the extent to which these emissions are predictable is investigated within the scope of this thesis. These data are recorded using a Euro 5 BMW F31 passenger under varying environmental conditions on Upper Austrian urban and rural roads and on motorways. A portable emission measurement system, AVL MOVE, provides a possibility to capture these intricately measurable quantities.
Different emission modeling approaches are implemented and evaluated. A standard look-up table method derived from test bench experiments is compared to more complex dynamic model classes. The first thereof, nonlinear ARX identification contributes to a broader examination of the connection between on-line measurable vehicular variables and exhaust pipe emissions. A polynomial class (PNARX) is used for obtaining linear-in-parameter models to ensure the applicability of standard algorithms, such as least squares and sequential forward selection. A second approach, artificial neural network fitting, is compared with the aforementioned models in terms of dynamic and stationary accuracy.

Introduction

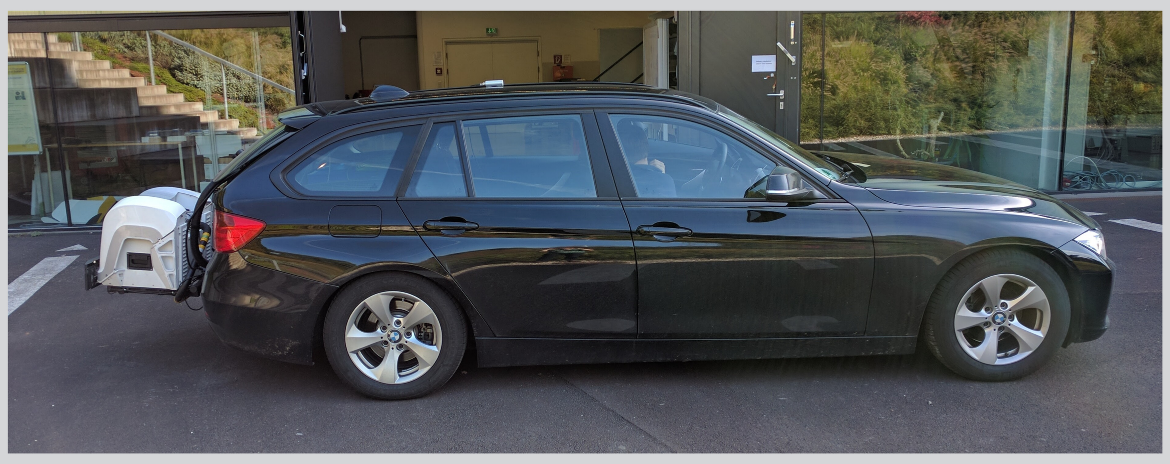
Since the introduction of Euro 3 emission norms the legal limits for emissions have been tightened. However, the deviation between the limitations and actual emissions increases. Especially nitrogen oxides' boundary values are exceeded by many modern diesel cars. Upcoming legislative changes concerning the admission procedure of light-duty vehicles necessitates closer investigation of actual on-road exhaust pipe emissions. Hence, in order to pass the future admission procedure, cars must fulfill the requirements of real driving cycles, rather than test bench measurements.

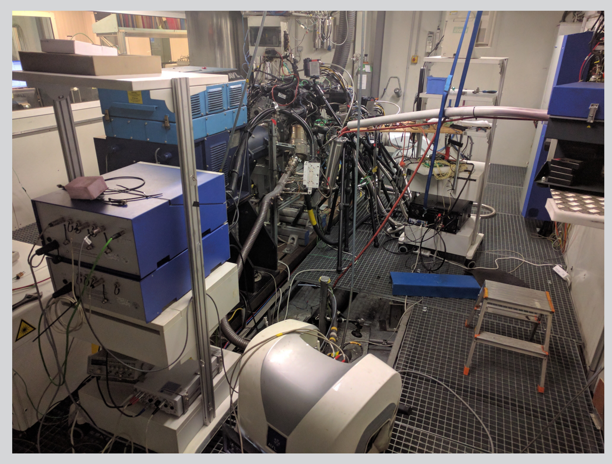


Legal limit NO_x emissions

Measurements

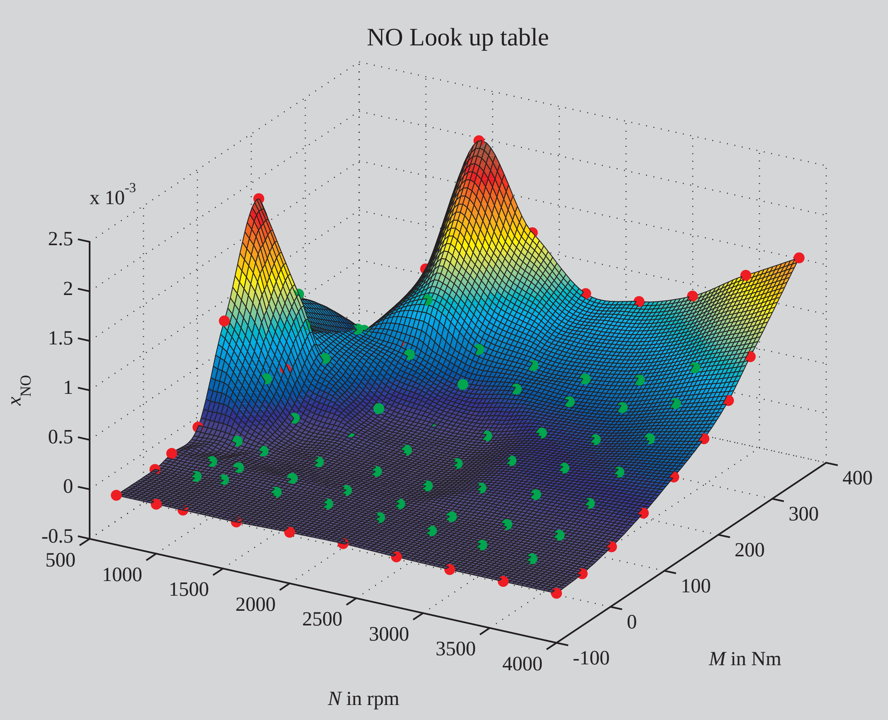
In order to investigate the transferability of test bench (TB) emissions and derive emission models based on these data, test cycles have been driven on the institute's experimental powertrain test bench (right picture). In addition, real driving measurements have been conducted using a Euro 5 BMW F31. Different types of cycles (urban, rural, highway) have been recorded as well as standard reproduction round-trips on the rural road from JKU to the village of Altenberg. The emissions have been captured with a portable emission measurement system (PEMS), AVL MOVE, attached to the tow coupling of the vehicle. The test bench was further equipped with additional emission measurement systems. CO_2 and NO emissions correlate well between RDE and TB, while NO_2 and soot deviate due to different states of the diesel particulate filters.





Baseline Method

The easiest way of estimating real driving emissions is by transferring TB data to real vehicles by applying two-dimensional look-up tables. The engine speed N and the load M have been recorded on the TB and serve as grid for the prediction of emissions (see figure). This method represents a standard way of assessing emissions and serves as a reference for more complex models. CO_2 and NO emissions can be predicted reasonably while NO_2 and soot emissions deviate due to system inequalities.



Polynomial Nonlinear ARX Model

A nonlinear ARX model based on RDE measurements should improve the prediction of on-road emissions. A nonlinear class of functions f_p, specifically polynomial functions, was selected and applied for system description, where p refers to the polynomial degree. A polynomial is made up of products of several different selected inputs and their delayed versions (entries of $\phi_{k,\text{lin}}$).

$$y_k = f_p(\varphi_{k,\text{lin}})^\top \boldsymbol{\theta} + e_k = \boldsymbol{\varphi}_k^\top \boldsymbol{\theta} + e_k \quad (1)$$

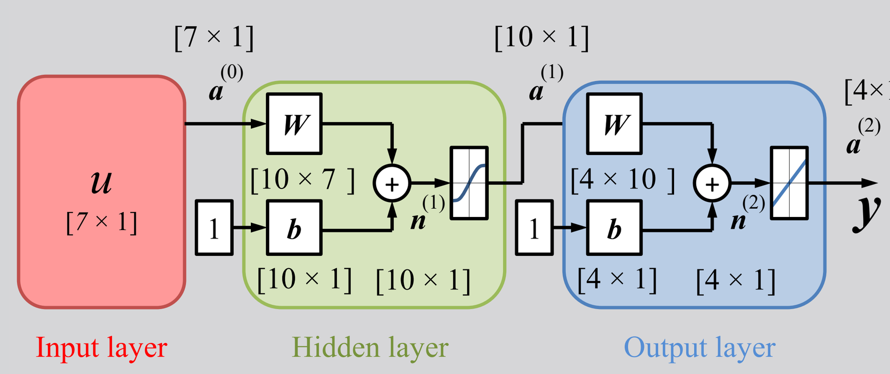
System parameters' estimations $\hat{\boldsymbol{\theta}}$ can be obtained by solving a least squares problem for regressor matrix $\boldsymbol{\Phi}$ and the output vector $\boldsymbol{y}$

$$\hat{\boldsymbol{\theta}} = \left(\boldsymbol{\Phi}^\top \boldsymbol{\Phi}\right)^{-1} \boldsymbol{\Phi}^\top \boldsymbol{y}. \quad (2)$$

The relevant entries of $\boldsymbol{\Phi}$ are selected by an input/output correlation analysis and a sequential forward regressor selection (SFS) algorithm beforehand. Additionally, model parameter such as polynomial degree and considered time delays have been optimized. Analyzing the results leads to the conclusion that engine torque and speed, exhaust gas temperature, injected fuel, inlet air flow, acceleration and road slope are most significant inputs.

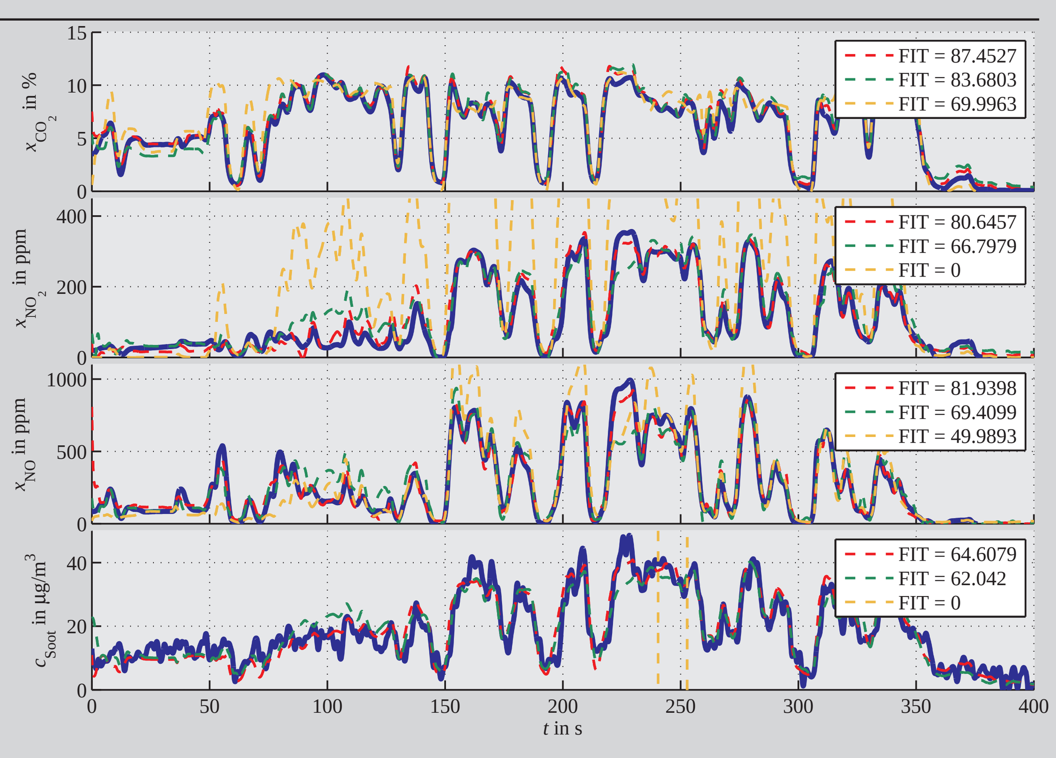
Neural Network

Artificial neural networks can approximate any nonlinear function and thus are used to establish a third model to be compared with the others. The optimized model parameters, like number of inputs and their delays, derived from the previous ARX investigations, are applied to the the neural network (NN) system class. After training a single hidden layer neural fitting network, a prediction model with decent estimating qualities is obtained. This model yields best results because compared to the others, it is not limited to a predefined function class, such as polynomials.



Results

The three different classes yield models with varying quality of prediction. The graphics to the right shows results for all relevant emissions on the Altenberg track as well as their FIT values in the legend. The baseline method is outperformed by both the ARX and the NN model, the latter of which is slightly more accurate in terms of dynamic trajectory estimation. However, the baseline fits well considering stationary processes. Regarding other criteria, like ease of applicability and comprehensiveness, the baseline and ARX models turn out to be better than NN. Thus, increasing modeling qualities come along with decreasing model simplicity. The choice which model to apply depends on the purpose of the investigation.



Measurement Baseline Nonlinear ARX Neural Network

Conclusion and Outlook

The transfer of test bench emissions to real drives comes along with some challenges that make it difficult to draw conclusions solely based on TB measurements. Different environmental conditions and the different states of diesel particulate filters are two examples thereof. The models derived from RDE data both yield well-fitting predictions but reveal a higher level of complexity. The introduction of stricter laws will make closer investigation of RDE and their accurate modeling indispensable.
These models can be used for establishing emission optimal autonomous driving strategies in order to decrease the environmental burden rather than the amount of burned fuel. The proposed algorithms for black box modeling and optimizing can further be applied to other scientific fields as well.