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Different Approaches to Soot Estimation as Key Requirement for DPF Applications

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ABSTRACT

The accuracy of soot estimation is - besides thermal management – one of the key requirements for successful DPF applications. With the implementation of more stringent emissions regulations and requirements for fuel efficiency the importance of high quality soot mass estimation becomes even more relevant. The durability targets for T2B5 and Euro 6 require accurate soot load detection under all driving profiles and customer specific environments – from low speed delivery cycles to high speed extra urban driving profiles. The most fuel and CO_2 efficient regeneration strategy relies on knowledge of the current soot mass in the DPF. This paper describes several options of soot mass estimation: From an empirical engine out emissions model, combined with a physical soot oxidation model to a physical model in which the pressure drop signal combined with other parameters is used to determine the filter load. Matlab/Simulink models were developed and evaluated for this study using test bench and real world vehicle driving data. This paper describes simple models used as well as the benefits and trade offs for each of the methods. It also provides data on the achieved accuracy in soot mass estimation for commercial diesel particulate filters used in light duty diesel applications.

INTRODUCTION

Diesel engines are one of the key technologies to cut greenhouse gas emissions effectively. Besides lower CO_2 emission they do have advantages in torque and performance versus gasoline engines. Those advantages helped the Diesel engine to gain market share in Europe to a current value of roughly 50%. The diesel particulate filter (DPF) for Light Duty Diesel passenger cars was introduced in Europe partially with Euro 4 as an optional accessory and as part of the self-commitment of the automotive industry [1]. With the implementation of Euro 5 all light duty diesel vehicles are expected to be equipped with a particulate filter to meet emissions standards. As the DPF is now required to meet the emissions targets together with new lifetime requirements there is a demand for more robust applications. Three different materials are on the market today: SiC, Aluminum Titanate and Cordierite. All of these filter materials have shown their capabilities to fulfill emissions compliance in various light duty diesel applications. Nevertheless the optimization of DPF applications with respect to efficient engine operation and DPF regeneration is still in progress. In this context, one key (control) parameter is the accurate knowledge of the actual soot load in the DPF at any time. This is due to two main reasons: “Overloading” with soot could lead to DPF damage whereas “underloading” results in unnecessary DPF regenerations and therefore CO_2 penalties. Advanced regeneration strategies depend on knowledge of the soot load, and use it as one parameter in order to define the target regeneration conditions. Higher soot loads for example require lower DPF inlet temperatures [2, 3]. The reliable application of such advanced operating strategies depends on an accurate soot mass estimation. Although significant progress has been made, the estimation of the soot load by open loop models or closed loop estimation based on a pressure

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difference across the filter is still subject to uncertainty. This is partly driven by the complexity of this task, limited resources for the application and calibration of complex models as well as inaccuracies in sensors (mass flow, temperature, and pressure) used for the estimation. In this paper we will discuss work related to the challenges of soot estimation under such real world boundary conditions. Different options for soot estimation were applied to a Euro 4 passenger car and programmed in Matlab/Simulink in order to investigate the advantages and disadvantages of each strategy. Extensive vehicle operation was used to generate baseline data for the development of the different types of soot estimation models through gravimetric measurement of the soot mass in the DPF during different driving modes. The intention of this work was to understand the real world accuracy which can typically be achieved by current sensing technology during highly transient vehicle operation, with different drivers in different driving profiles using relatively simple models with a minimum of required inputs.

FUNCTIONAL MODEL REQUIREMENTS

In this section the model approach will be discussed. All Matlab/Simulink models should be as simple as possible in order to run them in real time. This required the reduction of the input parameters to a minimum which makes it possible to run all tools via the MIP (Matlab Integration Package) during vehicle operation. The model was designed to consist of a combination of 3 independent sub models, including open and closed loop models. Model 1 (soot_dp) was assigned as a closed loop model with the attempt to determine the soot loading state of the DPF based on the pressure drop and volumetric flow signals. The approach taken for the second model (soot_ML) was to determine the soot loading state of the DPF based on the mode of vehicle operation. A pre-study was conducted in order to evaluate the different options of designing an open loop model which determines the DPF load based on engine operation or vehicle operation. The open loop model should be as simple as possible, using only a minimum of input parameters from the vehicle engine control unit (ECU) to allow real time usage.

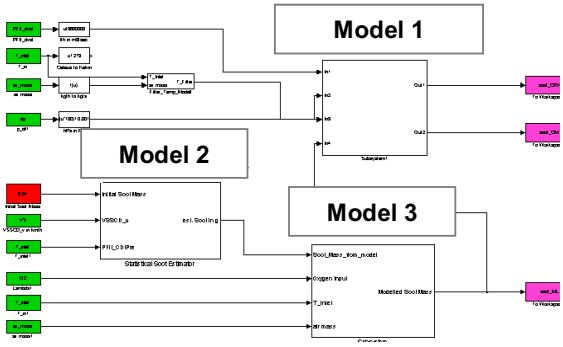

Figure 1. Overview Simulink model

Finally a third sub model was developed in order to determine the regeneration efficiency during periods of active regeneration. For that purpose the sub model was intended to use the DPF inlet temperature and all other relevant sensor-inputs from the vehicle ECU. This sub model is also an open loop model. The need for an accurate regeneration efficiency determination is driven by the need to maximize the distance between regenerations and minimize the time in regeneration. Both enable low CO2 emissions, good fuel economy as well as minimizing issues with respect to oil dilution by fuel. A generic overview of the entire Simulink model which was developed and applied is given in Figure 1. Details for each model and its application will be discussed later.

TEST VEHICLE AND HARDWARE USED IN THE EXPERIMENTS

The specifications of the vehicle used for the experiments are described in Table 1. The test vehicle had a close coupled DOC+CDPF after treatment system. The Aluminum Titanate (DuraTrap® AT ACT) CDPF used in this experiment had 5.66" diameter by 8" length contour (144 mm x 203 mm, 3.3 dm^3).

Table 1. Vehicle specifications

Vehicle weight	1600 kg
Emissions certification	Euro 4
Displacement	1560 ccm
# Cylinders	4
Power	80 kW
After-Treatment	DOC + CDPF

The CDPF had a 300cpsi, 13 mil wall thickness geometry and an asymmetric cell configuration (ACT), where the inlet channels offer more volume than the outlet channels [4].
The close coupled positioning of the CDPF was challenging for the weighing procedures. The exhaust system is located within the engine compartment with very little handling space around the components. Not only the difficult assembly of the DPF made modifications necessary – also the additional instrumentation added complexity. A couple of modifications were needed to get the CDPF removed within a short timeframe. The main modifications are: Adding additional flanges to the exhaust pipes that could be connected with V-Clamps and modification of the clamp that connected the exhaust system to the outlet of the turbine. Additionally all the heat shields that protect the engine compartment parts made from plastics were modified. The hoses for the pressure drop sensor were equipped with quick connectors to plug and unplug them without the usage of tools. The charged air pipes were modified to allow for easy access. In summary, with all the applied modifications the close coupled CDPF could

be removed within 5 minutes and re-assembled within 20 minutes compared to 1-2 hours that were needed with the unmodified system to only remove it. The weighing procedure itself followed a couple of strict rules. To get a good baseline value for the bare filter weight the canned filter has been heat-treated prior to the installation to stabilize the mat weight and remove all organics present in the mat. During operation the vehicle was not allowed to cool down prior to the CDPF weighing. Each time the same mechanic took care of determining the CDPF weight to minimize the variability coming from the operator. The balance used in our experiments was placed in an air conditioned room where the room temperature was constantly at 20°C. The balance was calibrated with a 10 kgs weight prior to each measurement. All relevant data around the weighing itself were recorded in a log book that contained data such as CDPF temperatures, mileages, time and of course the weights of the system. The CDPF-bed temperatures during weighing were usually > 190°C for the extra urban missions. For the city cycles the CDPF temperatures were usually between 140°C – 190°C at the time the system was placed on the scale - sufficient to avoid water adsorption by the hygroscopic soot and washcoat. The other main modification applied to our test car was the development ECU with ETK that replaced the series ECU. This kind of ETK ECU is mandatory to work with INCA and the MIP interface that allowed for ECU and Matlab/Simulink communication. The ECU and additional temperature data were recorded automatically and permanently with a Drive Recorder. The advantage of the Drive Recorder versus INCA is that all data is recorded automatically without the risk of data loss caused by operator mistakes. This allowed 2 shift operations without restrictions. The calibration of the models and especially the look up tables was done with the recorded data that was post processed in order to develop the Matlab/Simulink tools. All relevant model input parameters were acquired via the sensors that are part of the current EU4 hardware configuration of the vehicle and used by the production ECU for sensing. All additional sensors, that we had installed, such as oxygen sensor and thermocouples, were only used to monitor the system and to determine the DOC and CDPF exotherms. A sketch of the DOC/DPF instrumentation is given in Figure 2.

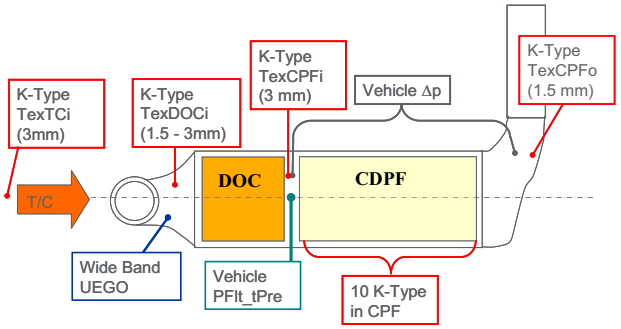

Figure 2. Additional DOC + CDPF instrumentation

CALIBRATION DRIVING CYLES

Table 2. Overview driving cycles

Mission	km	inlet in °C	Avrg. Km/h
Highway	3000	280	85
Extra Urb.	2000	240	48
City	1000	200	23

The experimental data base to develop and calibrate the Matlab/Simulink soot estimation models were generated during a 6000 km on road driving program in which the vehicle was operated in 2 shifts (each shift 7 hours net driving time). Three different driving modes (Highway, Extra Urban and City) have been used to get the required information for all typical driving conditions that a vehicle usually encounters. During those driving cycles more than 100 different labels have been recorded. The average vehicle velocities and CDPF inlet temperatures for the applied driving cycles are summarized in Table 2. In Figures 3 to 5 examples of the vehicle transients are given. Each of the diagrams includes air mass flow (AFM), vehicle speed in km/h and CDPF inlet temperature (T_Pre) in °C.

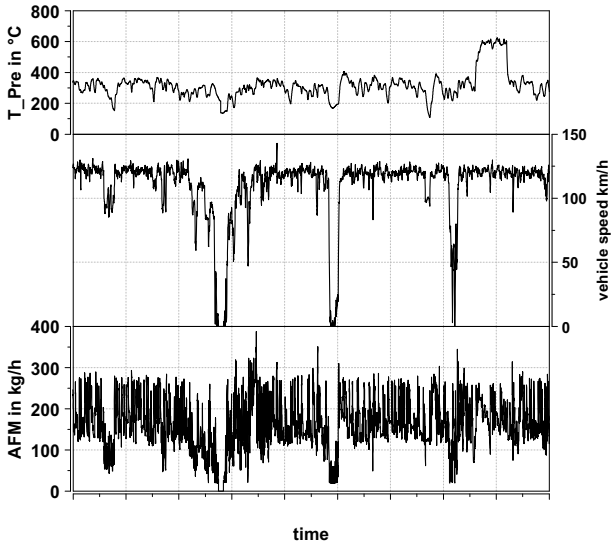

Figure 3. Typical highway driving

Typically highway driving is characterized by relatively high exhaust gas temperatures in the range where passive regeneration can occur. One can see from the diagrams in Figure 3 that even at relatively constant velocities the air mass flow and temperatures pre CDPF behave transient. This is resulting mainly from different road profiles with uphill and downhill grades, as well as from “nervous drivers” working with the accelerator pedal.

In difference to highway driving the extra urban driving is characterized by a wider spread of different speeds and temperatures. An example of typical extra urban driving is given in Figure 4. Extra urban missions can include all kind of roads - except highway. An extra urban cycle can include similar speed/load operation than highway cycles but usually the times where the vehicle is operated at steady conditions are very limited.

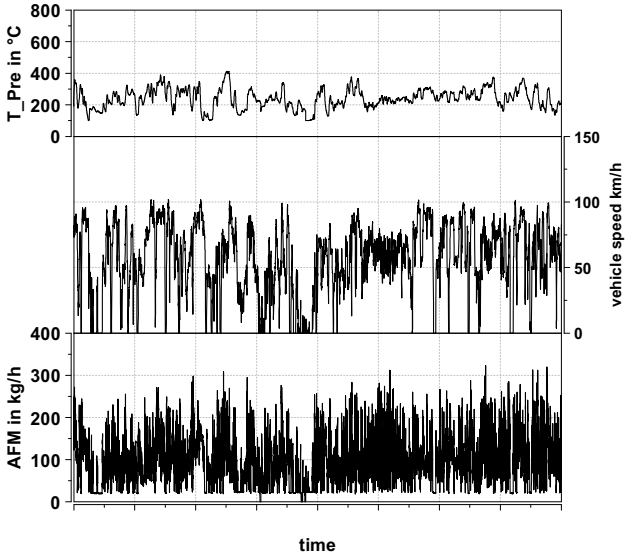

Figure 4. Typical extra urban driving

From Diagram 5 one can see that city cycles are designated by multiple stops and therefore resulting in accelerations with air mass flow peaks. The ECU sensor (T_Pre) plotted in Diagram 5 has its zero-point at 100°C. This limitation from the PT100 sensor has been ignored intentionally to understand if this limitation impacts the ability to develop models using current sensors.

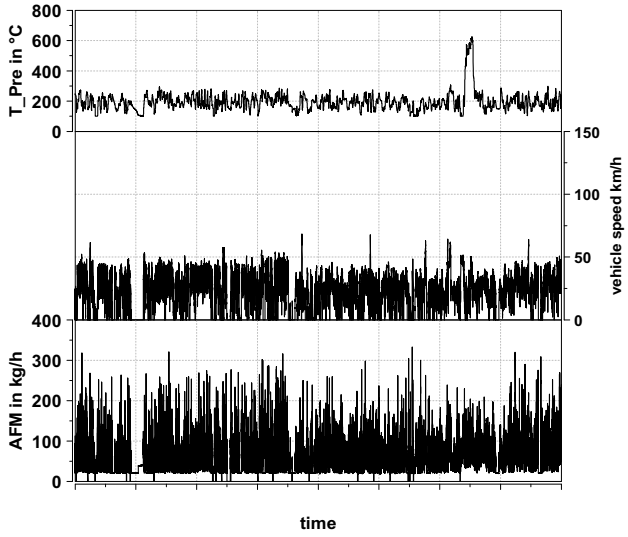

Figure 5. Typical city driving

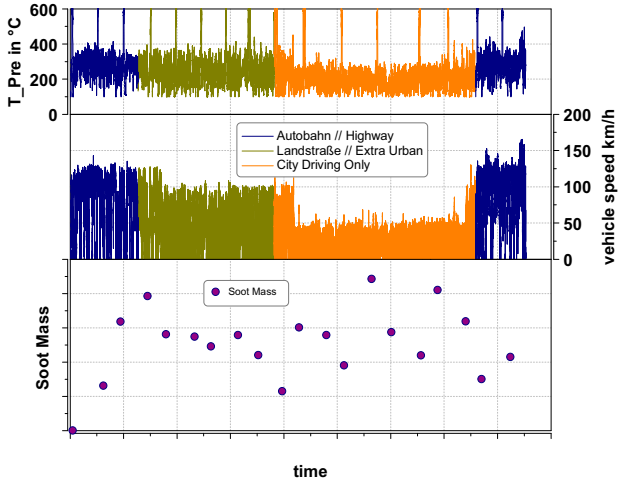

Figure 6. Driving and weighing data

After completing the on road driving program with regular filter weighing the CDPF has been deep cleaned using a manually forced regeneration with increased inlet temperatures. This was done to determine again the clean weight without any soot. The difference between this measurement and the initial clean weight equals the amount of ash that was accumulated in the CDPF. All weighing results were corrected for the amount of ash afterwards. The data gained from the driving program was used to calibrate and evaluate the models mentioned above. The vehicle speed, CDPF inlet temperature and results from CDPF weighing are summarized in Figure 6.

CLOSED LOOP FLOW RESISTANCE MODEL

FUNDAMENTALS

In the absence of a direct feedback of the soot emitted by the engine or accumulated by the filter the measurement of the pressure drop response of the DPF is the only signal that allows for some closed loop feedback. The challenge in this is that the pressure drop response of the filter is determined by several factors and the result of several phenomena. In general the pressure drop across a DPF is determined by five contributions:

1. Inlet effects due to contraction of the gas flow and development of the flow profile inside the channels
2. Friction along the inlet channels
3. Losses due to the resistance to flow through the wall and soot layer
4. Friction along the outlet channels
5. Outlet effect due to the expansion of the gas flow

Only contribution (2) and (3) are affected by the soot and can be used for the estimation. The effect of the soot on the friction is arising from the soot layer that restricts the inlet channel opening. The effect of the soot on the resistance of the wall (inverse of effective permeability) is more complex and determined by the combined effect of the change of two phenomena. On the one hand the change in wall permeability due to the soot deposited inside the walls as result of deep bed filtration and, on the other hand, the permeability of the soot layer itself, which develops as result of cake filtration on top of the filter wall. Generally, the effect of the soot inside the wall results in a significant increase in pressure drop for a given amount of soot. It is, however, limited by the amount of soot that is actually penetrating into the wall. The response of the soot accumulated as layer on top of the walls is over a reasonably wide range of soot loadings approximately linear with soot mass and proportional to the thickness of the layer.

Generally the impact of the deep bed filtration of soot has been found to be minimal during actual use once a small amount of ash has been accumulated [4]. This is due to the observation that the ash forms a very thin membrane layer which has minimal effect on the permeability but prevents the soot from penetrating into the wall structure. As this is important for the application of pressure drop based models, this will be discussed in more detail in the subsequent sections.

Effect of deep bed filtration on pressure drop

As mentioned above is the pressure drop response of soot loaded DPFs dependent on where the soot is deposited, e.g. on the wall vs. inside the wall structure. Both phenomena can be observed on new (unconditioned) DPFs that don't have an ash-membrane minimizing the penetration of soot into the CDPF wall [4]. The effect of this phenomenon is described in Figure 7, where pressure drop as a function of soot load is compared for DPFs with and without the effect of deep bed filtration. Those phenomena need to be considered when applying a pressure drop based soot estimator.

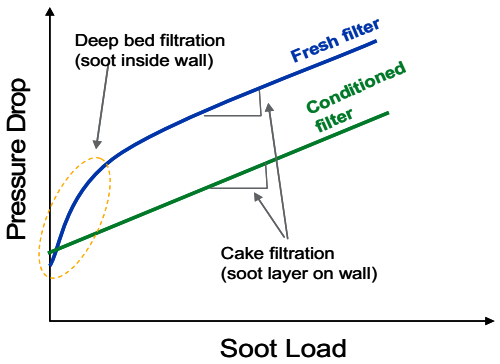

Figure 7. Deep Bed Filtration (schematic)

A certain conditioning procedure needs to be applied to "calibration samples" prior to determining the flow resistance of a soot loaded DPF. In some studies models were introduced that are capable to calculate the portion from deep bed filtration on pressure drop [5, 6]. For this study we did not incorporate this phenomenon as it is only observed with "unconditioned" samples. Another reason not to incorporate deep bed filtration is resulting from "partial" regenerations that are observed for catalyzed filters, where an active catalyst removes the soot particles accumulated in the wall due to "partial" NO_2 regenerations. The complexity of deep bed filtration would definitely require too many assumptions and was therefore neglected. Instead we decided to apply a test bed conditioning procedure to the CDPF that was used in our experiments. A typical method to minimize deep bed filtration and its impact on pressure drop calibration samples is shown in Figure 8. Plotted is the relative flow resistance of the DPF (Y- axis) vs. soot load (X-Axis).

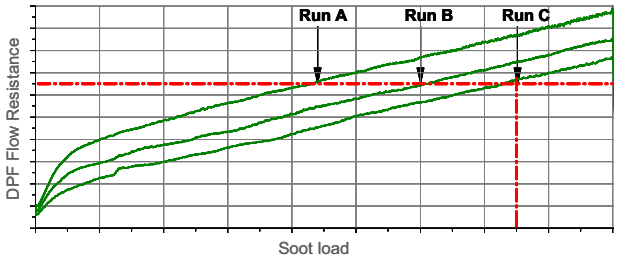

Figure 8. Impact from DPF conditioning cycles on flow resistance - engine test-bed data

Between each of the 3 soot loading cycles a four hour conditioning cycle was applied with the engine being operated at full load for 3 hours, followed by 1 hour of active regeneration mode. Purpose of this conditioning mode is to cover the CDPF inlet channels surface area with a thin ash membrane resulting from oil consumption. One can see that the "knee" (describing the disproportionately high flow resistance increase for low soot loads) decreases between each of the 3 soot loading cycles.

CLOSED LOOP MODEL APPROACH - MODEL 1

In this section Model 1 that is used to estimate the CDPF load based on pressure drop will be discussed. The nomenclature for the closed loop model (Model 1) is soot_dp. Three sensor inputs are used:

1. Pressure drop signal across CDPF (PFlt_pDiff),

2. Air mass flow from the air mass flow meter (AFM) and

3. Temperature pre CDPF (T_Pre) from the PT100 ECU sensor.

Model 1 (soot_dp) uses reference curves for an empty and soot loaded CDPF and correlates the measured pressure drop from the ECU sensor to the pressure drop of a “virtually” clean and “virtually” soot loaded CDPF. The reference pressure drop curves given in Figure 9 that were used for this model-approach were generated on an engine test bed using the same type of engine and same type of exhaust system. The current CDPF loading state is determined according to Equation 1. Certain filters and algorithms were applied to smooth out the transient pressure drop response.

One observation during the development of Model 1 was that there are conditions during vehicle operation that are very critical for pressure drop based soot estimation - typically at low volumetric flows very small changes in delta p can lead to massive changes in the estimated soot load as the clean and soot loaded reference curves are close together. Another area of uncertainty is coming from temperature effects impacting the pressure drop over the CDPF. There are different options to handle those physical limitations. One option would be to ignore those values gained below pre-defined thresholds – or apply switches that change the soot estimation mode from flow resistance to the empirical engine out model, discussed in the next section. Those switches are defined as “Quality Gates”.

$$Soot\ Load\ [\%] = \frac{\Delta p - Crv_\Delta p_{Clean}}{(Crv_\Delta p_{SootLoaded} - Crv_\Delta p_{Clean})} \quad (1)$$

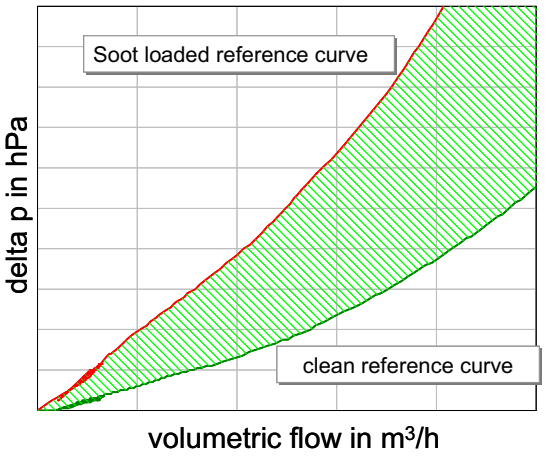

Figure 9. Calibration curves for flow resistance model (obtained with engine bench experiment)

OPEN LOOP APPROACH

FUNDAMENTALS

Another approach to soot estimation is to assume that engine out emissions are a function of engine-load and speed. It is quite easy to evaluate emissions at steady state conditions as shown in Figure 10 [7] where the soot emissions in g/kWh for a typical light duty diesel engine are plotted as a function of (steady state) load and speed. In that case an AVL Micro Soot Sensor was used to determine the engine out emissions. In a pre study it was attempted to use such a map to determine the soot concentration of the exhaust gas and using its numerical integral to determine the DPF load. The results were not satisfying for some reasons: The speed/load maps do not consider emissions that result from transient operation, and they do not take the number of load changes into account. Boulouchos and Kirchen [7] demonstrated an approach in which an originally crank angle resolved soot model [8, 9] has been reduced to a combustion cycle resolution soot model, using typical (average) values for all combustion parameters that are typically a function of crank angle. Those input parameters are: cylinder pressures, injection rates, temperatures or mass fraction burned rates. The averaged inputs were used in a model that calculates both, the formation and the oxidization of soot. This approach showed excellent agreement between measurement and model [7]. A significant drawback of such a model is the relatively complex parameterization that requires determination of transient engine out emissions besides stationary emissions.

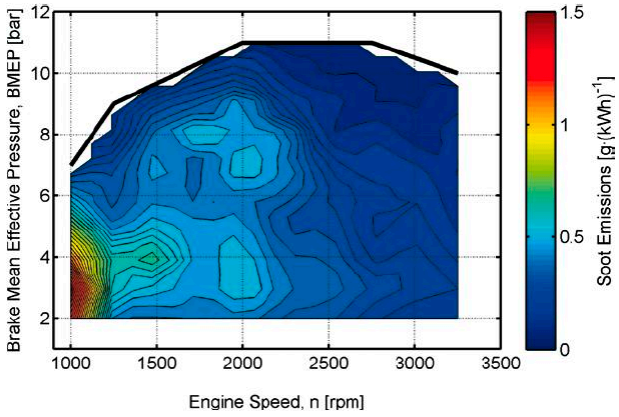

Figure 10. Soot Map of a typical LDD engine [7] determined with an AVL Micro Soot Sensor

IMPLEMENTED APPROACH – MODEL 2

Model 2 (soot_ML) developed in the work reported in this paper is based on a different, much more simplified approach that requires a minimum of sensor inputs and low calibration effort. Instead of describing the engine and its emissions Model 2 allocates emissions to typical driving conditions. This approach needs a few of assumptions. The main assumptions are: The higher the

average velocity, the less transient is the engine behavior, and transient engine operation is causing higher engine out emissions. This is due to a short term oxygen deficit which is contributed to a slow closing of the EGR valve and slow build up of the intake charge pressure with a simultaneous increase in the injected fuel quantity [7]. The acceleration smoke is a visually observed phenomenon for diesel vehicles without DPF. Therefore the amount of injected fuel was limited by so called smoke limit maps for vehicles without DPF. Another main assumption incorporates the passive regeneration that typically occurs during extra urban driving. This is captured through the second input parameter, the exhaust gas temperature. Using the weighing data from vehicle operation we determined typical soot loading rates. The soot loading rates that we determined were not split into the soot coming from the engine and the soot being removed by means of passive regeneration. The model assumes that higher inlet temperatures remove more soot by passive (NO_2) regeneration therefore the soot loading rate decreases. The soot loading rates can be negative for very clean vehicles. However, in our case the vehicle was usually operated below the balance point. The balance point describes the driving mode where the CDPF soot load is constant - the amount of emitted soot equals the amount of soot oxidized. For pure highway driving we observed conditions in the region of the balance point where the DPF load did not increase as a function of driven mileage. Results for such an observation will be discussed later. The combination of those assumptions describes our approach. In brief, the developed Matlab/Simulink model does not use information about the point of engine operation (speed/load), rather the model utilizes information about the state of vehicle operation. The latter being defined by vehicle speed and exhaust gas temperature pre DPF.

Table 3. States of vehicle operation as a function of speed (Y-axis) and temperature (X-axis)

Breakpoints	Column	(1)	(2)	(3)	(4)	(5)
Row		0	100	200	300	400
(1)	0	1	2	2	2	2
(2)	20	1	2	2	3	3
(3)	40	2	2	3	3	3
(4)	60	3	3	3	4	4
(5)	80	3	4	3	4	4
(6)	100	3	4	4	4	5
(7)	120	4	5	4	4	5
(8)	130	4	4	5	5	5

To further simplify the model, the speed temperature map was reduced to 5 different states of operation, as shown in Table 3, ignoring that there might be infinite changes in engine-out emissions as a result of different operational modes. An indication that average values of different passenger cars are very similar is that e.g. EU4 legislations (0.025 g/km) were fulfilled w/o DPF from many different OEMs at nearly identical Particulate Matter (PM) values. Randomly picked emissions data [10] are plotted in Figure 11 (non DPF EU4 passenger cars only).

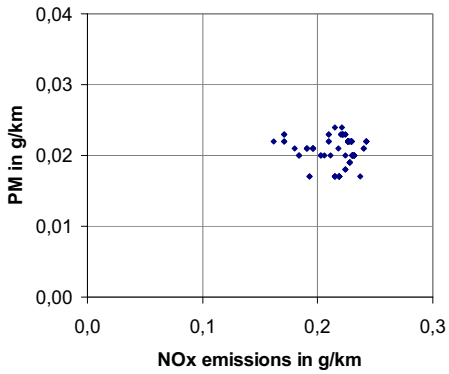

Figure 11. NO_x/PM NEDC-data EU4 passenger cars without DPF [10]

To summarize the approach and its underlying assumptions: The correlation between low average speed and low exhaust gas temperature is yielding to high engine out emissions (in g/km) whereas the combination of high average speed with high average CDPF temperatures (ideally between 250°C and 400°C) is leading to low engine out emissions and passive regeneration. To obtain information about the soot loading rate, each of the states of vehicle operation (1-5) introduced above is assigned to a certain engine out emissions in grams per kilometer. This is achieved by another map in the Simulink model. An emissions test over the NEDC cycle in which the raw emissions without CDPF were measured was used to obtain additional data for the vehicle. These data combined with the weighing results from the driving tests were used to calibrate the model. An example of the comparison between estimated soot mass from Model 2 (soot_ML) and measured soot mass during vehicle operation is given in Figure 12.

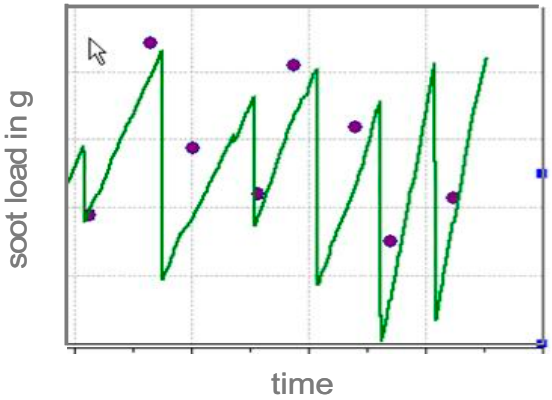

Figure 12. Comparison of open loop model (Model 2, soot_ML) and measured soot mass (markers)

OPEN LOOP SOOT OXIDATION – MODEL 3

In this section Model 3 will be described – the soot oxidization sub model. Purpose of this model is to determine the efficiency of a regeneration event as accurate as possible to allow an assessment of the required regeneration duration or of the remaining soot mass if the regeneration duration is fix-timed.

There are 4 key parameters determining the regeneration efficiency, as discussed in reference [2]: soot mass on the filter, oxygen concentration, DPF inlet temperature and mass flow of the exhaust gas. Three of these parameters are incorporated into the oxidation model. The sub model uses the ECU inputs from the air mass sensor, temperature sensor pre CDPF (T_Pre) and oxygen from an UEGO-device. If no oxygen sensor is available the oxygen content can also be estimated with the AFR (Air Fuel Ratio) using air mass flow and injection quantities from the ECU. This also represents the fall back position in case of sensor failure. The impact from the actual soot load on DPF regeneration temperature and therefore regeneration efficiency is neglected. In addition to the current map based approach a 0-D model was programmed and tested. However it was found to be too slow on the hard-/software used.

The applied sub model exists of basically 2 maps (look up tables) which determine a soot combustion rate. In the main map the soot combustion rate is obtained as a function of inlet temperature (T_Pre) and air mass flow (AFM). The basic soot burning rate data calibrated into this map have been generated with an engine bench experiment [2]. To consider the effect of the exhaust gas oxygen content the soot oxidation rate obtained from the first map is corrected by use of a factor obtained from a second map. This factor considers that higher oxygen levels accelerate the reaction, while lower oxygen rates reduce the oxidation rates. Finally the time integral of the soot burning rate values is subtracted from the estimated soot load obtained from the open loop model, soot_ML.

RESULTS

In this section the results are discussed that were obtained with the different Simulink models described in the previous sections. Each model is analyzed for its accuracy and compared with the results from weighing.

CLOSED LOOP RESULTS – MODEL 1

The diagrams in Figure 13 are showing a transient response of the closed loop soot model (soot_dp). The diagram in Figure 13 includes the CDPF inlet temperature from the PT100 sensor (top row), the vehicle speed in km/h (middle row) and the estimated soot from the closed loop model (bottom row).

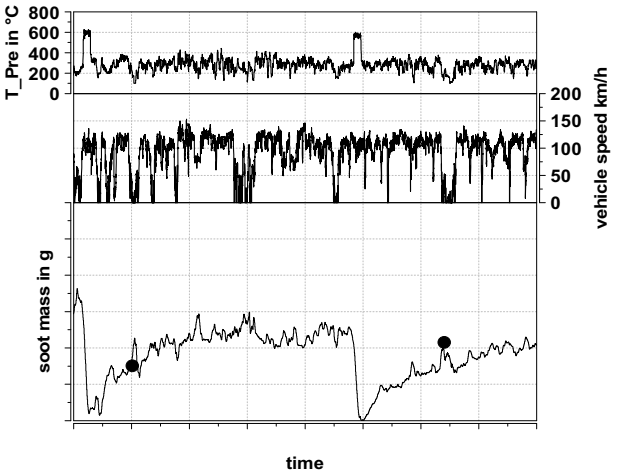

Figure 13. Transient results from the closed loop model (Model 1, soot_dp) and measured soot mass (bottom row. markers) during highway driving

From the results one can see that the highway driving was interrupted to determine the weight of the CDPF. During those low speed passages to the testing facility the quality of the signal was different to the quality that we could obtain under highway driving conditions. Nevertheless, the results indicate that the vehicle is partially operated in areas where the emitted and removed soot (by passive regeneration) are balanced. The summary of the achieved accuracy is plotted in Figure 14. The delta is calculated as follows:

delta in g/l = soot mass measured – soot_dp

Figure 14. Deviation between Simulink Model 1 and results from CDPF weighing for the closed loop model (soot_dp)

The gained results are differentiated for the 3 different driving modes. The accuracy is roughly within +/- 1 g/l except for the city cycles. In this case the observed deviation was as high as ~ 2.5 g/l. This is explained by low volumetric flows and pressure drop values with the earlier described negative impact on accuracy on the one hand, but on the other hand a potential change of

the soot properties has to be considered. Typically the HC content of the soot is increasing with lower average inlet temperatures.

OPEN LOOP RESULTS – MODEL 2+3

The open loop model (soot_ML) that uses the incorporated soot combustion model was analyzed analogous to the closed loop model. In Figure 15 an example for an interrupted city regeneration is plotted. The diagram contains (from top to bottom): Inlet temperature (T_Pre); Vehicle speed and estimated soot load from the open loop model (soot_ML).

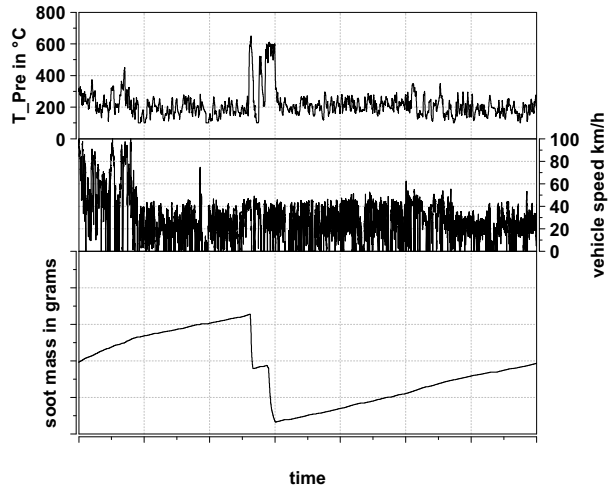

Figure 15. Example for open loop model (Model 2, soot_ML) transient during city cycling

One can see that the soot combustion model does not "reset" the soot model value to zero; it is capable to determine a partial or interrupted regeneration and would be usable to trigger optimized regeneration timing

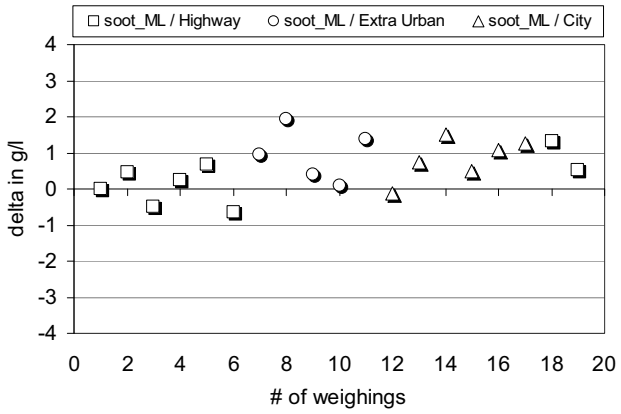

Figure 16. Deviation from SIMULINK Model 2 (soot_ML) and measurements – positive values represent underestimation by the open loop model

The overall accuracy that was achieved with the open loop model (soot_ML) throughout the driving program is given in Figure 16. it was roughly within +/-2 g/l. The best accuracy was achieved for highway missions, where most of the measurements were within +/- 1 g/l.

COMBINED APPROACH RESULTS – MODEL 1+2+3

As mentioned above did we identify critical conditions for the approach to determine the CDPF loading state based on its flow resistance. One approach was therefore to define those conditions and switch then between both of the models (open - and closed loop) based on the quality of the signals. The nomenclature for the soot mass being estimated from the combined models is soot_CM.

The switches that choose either the signal from Model 1 (soot_dp) or Model 2 (soot_ML) are defined as quality gates. There are three calibratable switches between both models. The three gates are: pressure drop, CDPF temperature and a soot loading rate per time ($\Delta SL/\Delta t$). The advantage of this approach would be an increased accuracy and the option to detect engine emissions drift. An example for the combined approach is given in Figure 17.

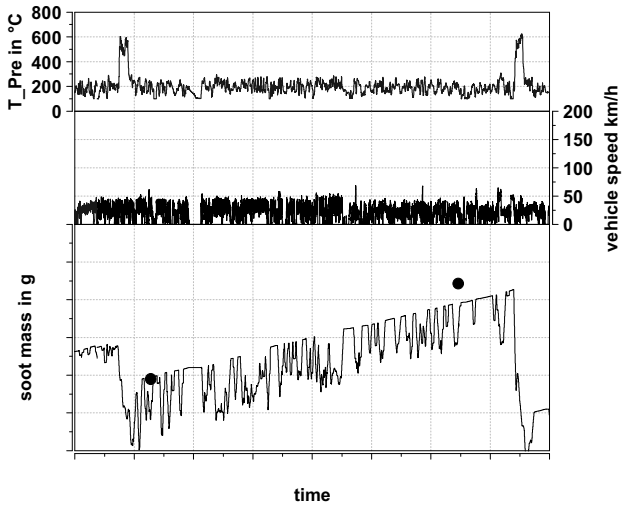

Figure 17. Example for the combination of all 3 model approaches – trace of soot_CM during city driving together with results from weighing (markers)

The diagram contains temperature pre CDPF (T_Pre, top row), vehicle speed in km/h and the combined model (soot_CM) trace (bottom row) together with two results from CDPF weighing (markers, bottom row). From the diagram one can see how the estimated soot mass alternates between soot_dp (lower limit) and soot_ML (upper limit). The open loop model (soot_ML) value was closer to the measured CDPF weight – therefore the overall accuracy could be improved. Summarized results are given in Figure 18. The analysis is analogous to those made for the two other approaches soot_dp and

soot_ML. Again, the positive deviations are describing underestimation by the combined model soot_CM. Looking at those results an accuracy of +1.5/-1 g/l for this combined approach was achieved.

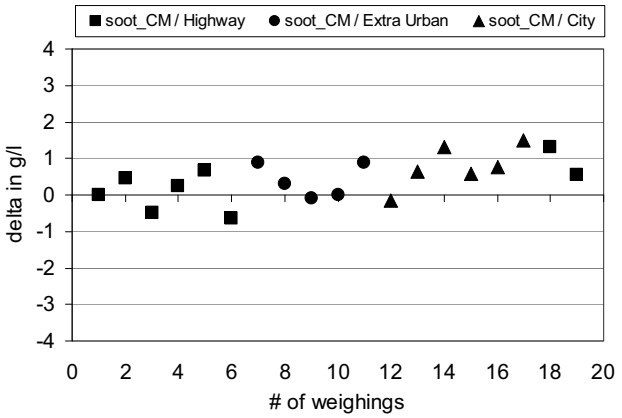

Figure 18. Results for the combination of all 3 models (soot_CM) / positive values represent underestimation

CONCLUSION

Two different approaches to soot estimation were evaluated in this study. In one approach the flow resistance of the CDPF was used to determine its state of loading, in the other approach an open loop model that assigns emissions to 5 different modes of vehicle operation has been programmed and calibrated. Both models were fitted with data gained from a 6000 km driving program that delivered typical vehicle data for 3 different driving profiles. The open loop model (soot_ML) was combined with a map based soot combustion model that determines the soot burning rate as a function of inlet temperature and air mass flow. Correction maps for different oxygen contents were developed to further increase the achieved accuracy. The effects of passive regenerations are considered by this approach as real world soot loading rates were used for the calibration. The accuracy that we observed was in ranges that would allow save DPF regeneration under all 3 driving modes. To further improve an open loop model, deterioration factors and algorithms that are capable to detect emissions drift would be required. Fuel injectors, air flow meters, EGR-valves and EGR coolers are potential root causes for the change of raw emissions as a function of time. Such drift detection would be to complex for this simplified approach to soot estimation. In our study this role has been given to the flow resistance model that uses physical inputs from 3 vehicle sensors to determine the CDPF loading state. One conclusion from the development of the soot_dp model was that different driving profiles impact the ratio of soot mass to flow resistance. Typically the same gravimetric amount of city soot created a lower differential pressure across the CDPF compared to soot resulting from extra urban missions that was trapped under condition where the exhaust gas temperature was higher. To compensate such observed phenomenon a potential solution would be to add another soot loaded reference curve that was generated under conditions that are equivalent to city driving (low exhaust gas temperatures and partially inactive DOC). Based on a calculated CDPF temperature the model could switch between the two reference curves.

Another potential solution was demonstrated by combining the closed and the open loop model. In general such a combination is recommended as it provides the option to use each of the approaches in the areas in which they work best. It also maintains a closed loop feedback - enabling drift or failure detection of components - which can not be detected by open loop models as stand alones.

The accuracy achieved by our simple model is very promising, knowing that it can be enhanced for example by using more sophisticated filtering tools for the measured parameters or increased calibration efforts (which would be typical for a series application). In addition, a high cell density (300cpsi) filter with asymmetric cell technology was used, which is recommended for high ash storage capacity but which also is challenging for soot detection due to the relatively shallow slope of the pressure drop vs. soot load relationship. It should be mentioned that the work done did not include the variations between hardware components.

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NOTATIONS AND ACRONYMS

Δp	Differential pressure drop across CDPF
Crv_dp_{Clean}	Empty pressure drop reference curve
$Crv_dp_{Soot\ Loaded:}$	Soot load. pressure drop reference curve
AFM	Air Flow Mass
CDPF	Catalyzed Diesel Particulate Filter
DOC	Diesel Oxidation Catalyst
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
EU	European Union emissions legislation
ETK	Emulator Tast Kopf
INCA	Integrated Calibration and Acquisition System
NEDC	New European Driving Cycle
T2B5	US Tier 2 Bin 5 emissions legislation
UEGO	Universal Exhaust Gas Oxygen