2005-01-3852

Transient emission predictions with quasi stationary models

Claes Ericson, Björn Westerberg
Scania CV AB

Rolf Egnell
Lund Institute of Technology

ABSTRACT

Heavy trucks contribute significantly to the overall air pollution, especially NOx and PM emissions. Models to predict the emissions from heavy trucks in real world on road conditions are therefore of great interest. Most such models are based on data achieved from stationary measurements, i.e. engine maps. This type of “quasi stationary” models could also be of interest in other applications where emission models of low complexity are desired, such as engine control and simulation and control of exhaust aftertreatment systems.

In this paper, results from quasi stationary calculations of fuel consumption, CO, HC, NOx and PM emissions are compared with time resolved measurements of the corresponding quantities. Measurement data from three Euro 3-class engines is used. The differences are discussed in terms of the conditions during transients and correction models for quasi stationary calculations are presented.

Simply using engine maps without transient correction is not sufficient. For the engines studied, accumulated errors of up to 60-70% are common before correction. Earlier work in this field has mainly been focused on statistical correction models of accumulated emissions. The transient correction model presented in this paper uses stepwise correction and has a physical interpretation. The delay introduced by the turbocharger during transients results in lower air flows and hence lower air-fuel ratios, than predicted from engine maps. A delay time and a corresponding transient air-fuel equivalence ratio (λ) is estimated in each time step and is used for compensation of the emissions.

Another important aspect of models for simulating real world emissions is generality, whether a common emission model can be used for all engines of a given emission classification. Differences between the engines in this study are discussed.

INTRODUCTION

Simple models for predicting the emissions and fuel consumption of heavy trucks are useful in many applications. The type of models used in this paper are “quasi stationary” which means that they use engine maps generated from data measured during steady state test bed conditions. COST 346 is a European project concerning the availability of heavy duty engine emission data. Existing data from engines measurements have been collected and new measurements of more recent engines have been performed according to a coordinated and standardized programme. One of the main goals is to collect a common database for steady state emission maps.

Hausberger (1,2) presents an overview of the real world emissions simulation problem and previous work in the area. Two different concepts for transient correction of quasi stationary emissions are presented. The TUG-PHEM transient correction model relates the difference between measured and quasi stationary values to engine power. Using multiple regression analysis an additive black box compensation function is developed. The results with this type of transient correction are somewhat mixed. In some cases the error is actually increased after transient correction. It should be noted that the engines studied are certified for Euro 2. Experience have shown that much less transient correction is needed with pre Euro 3 engines than more recent engines because of less active control of the injection angle. The second model called TNO HD Testcycle includes a multiplicative compensation based on the vehicle driving cycle. A link between the RPA (Relative Positive Acceleration) of the test cycle and the need for transient correction is observed. Both models correct the accumulated emissions over a transient cycle. No time resolved measurements of particulates are studied.

A similar correction model to the RPA correction was presented by Egnell (6). It is based on the degree of transience, defined as the number of times the time derivative of the fuel mass flow is larger than a specific value. A second order polynomial relation between measured/simulated ratio and degree of transience is used to compensate the emission factors.

Results for CO compensation during 26 testcycles using a Euro 3 class engine are good (Figure 1). The model compensates accumulated values only however and has not been validated on particulate emissions.

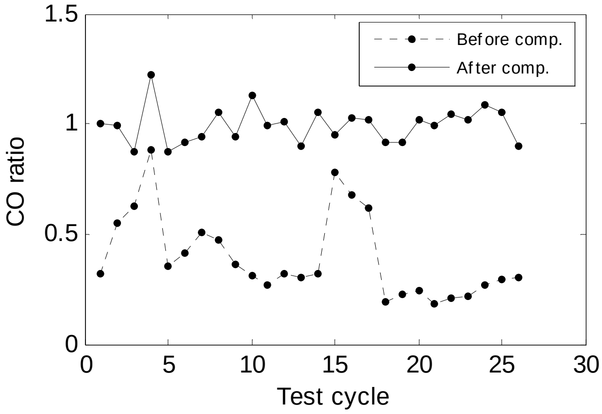

Figure 1 Accumulated ratio simulated/measured CO before and after degree of transience compensation

Vora et al. (4) have studied multiple driving cycles and developed simple models to correlate the emission factors between the cycles. The turbo lag which results in a particulate peaks during transient operation is identified as a major contributor to overall PM emissions. Differences in emissions between engine generations are observed, and are explained by active control of the injection timing outside the test cycles in more recent engines.

The models developed in this paper are primarily useful for predicting emissions from heavy trucks during real world conditions, but can also be used for engine control and simulation and control of exhaust aftertreatment systems. The challenge with quasi stationary models is that transient correction methods must be developed to get good results during transient test cycles and real world driving. In order to make the models generally applicable, only torque and speed must be used as inputs to the correction models. This paper is focused on making a physical interpretation of why correction is needed and the development of such a transient correction model.

EXPERIMENTAL DATA

Measurement data from three 12-litre turbocharged heavy truck engines certified for Euro 3 is used. The engines are referred to as Engine A, B, C. Two different fuels have been used, Swedish EC1 fuel and AVL-TUG reference fuel. The focus in this article is on the data using EC1 fuel, although differences in emissions (depending on the fuel used) exist which will be discussed further.

A total of approx. 100 steady state operating points are included. This data set includes the ESC and ECE R49 test cycles, a full load curve as well as some extra points chosen to complement these cycles.

The time resolved measurements uses a sampling rate of 1Hz. The data set includes four transient test cycles, the ETC and the TNO real world driving cycle part 1-3. The average values of two consecutive runs of each transient cycle are used. A TEOM instrument is used to measure time resolved particulate emissions. Unfortunately the equipment used has a much slower dynamic performance than for example the instrument used for measuring NOx. This makes validation of a particulate emissions transient correction model difficult. The integrated TEOM particulate values show good agreement with the filter values however.

To complement the slow TEOM measurements, smoke opacity measurements from an engine (engine D) similar to engine A are also used. The engine hardware is identical, but a higher injection pressure and a different mapping are used in engine D which results in lower overall particulate levels. The sampling rate in this data set is 10Hz and one test cycle is included, the ETC.

QUASI STATIONARY CALCULATIONS

Based on the steady-state data collected in test beds, engine maps for NOx-, CO-, HC and particulate emissions as well as air-fuel equivalence ratio (λ), air mass flow rate and fuel mass flow rate are created. The inputs to these maps are torque and speed. Hausberger (1,2) uses maps normalized with rated power in order to make them comparable for different engines sizes. In this article, all engines are of similar size and rated power, making normalization unnecessary. An example of a NOx-map for a Euro 3-class engine is shown in Figure 2.

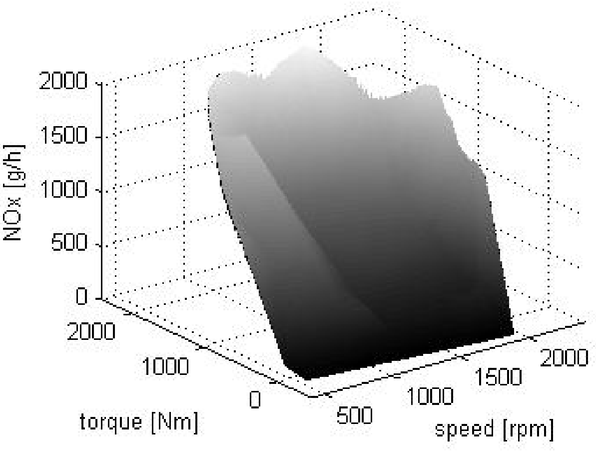

Figure 2 NOx map, engine A, before extrapolation

Using the engine maps, quasi stationary emissions and fuel consumption during transient test cycles can be calculated. The advantage using engine maps for simulating emissions is the low complexity; all that is needed is a simple interpolation in each time step.

Some operating points during transient test cycles (and real world driving) fall outside the engine maps. This will result in indefinite values in these points. The obvious solution to this problem would be to run more steady-state measurements to cover a wider range of torque and speed. It is convenient however to use existing databases of steady state test bed data, therefore extrapolation of the generated maps is used. Various extrapolation methods have been tested, the conclusion is that most general methods such as spline extrapolation generates non-physical results (negative emissions for example). The best results have been achieved with semi-manual extrapolation. With the steady state data available in this case, the majority of the operating points in the test cycles fall within the convex hull (typically 90% for the ETC cycle) and the rest of the points are fairly close to the boundary. For simplicity reasons hold-end-value extrapolation is used, integrated results over the test cycles shows negligible differences between the semi-manual and the hold-end-value extrapolation methods.

TRANSIENT CORRECTION

The ratio of quasi stationary calculated emissions and fuel consumption over measured values is shown in Table 1 (accumulated results over all four transient test cycles).

	Fuel consumption	**NOx**	**CO**	**PM**	**HC**
Engine A	0,96	0,90	0,61	0,70	1,54
Engine B	0,98	1,11	0,36	0,45	1,47
Engine C	1,03	0,79	0,52	0,50	1,30

Table 1 Accumulated ratio simulated/measured

The fuel consumption is well predicted using engine maps without transient compensation, within 4% for all engines. Figure 3 shows measured and simulated fuel mass flow in a sequence of the ETC cycle. No transient correction is needed.

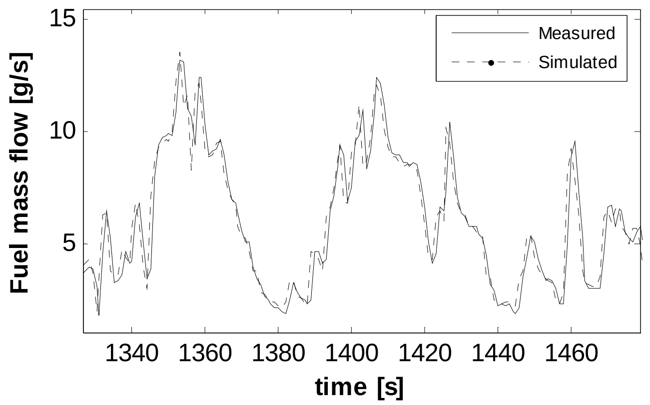

Figure 3 Measured and simulated QS fuel mass flow, engine B, sequence of the ETC

Simulated NOx emissions show fairly good correspondence with measured values, although substantial differences exist between the engines. The difference is most obvious during transients (Figure 4). One explanation for this could be that the control systems use active control of the injection timing during transient conditions. This type of “dynamic mapping” is not consistent between the manufacturers making a general NOx transient correction model using only torque and speed as inputs difficult.

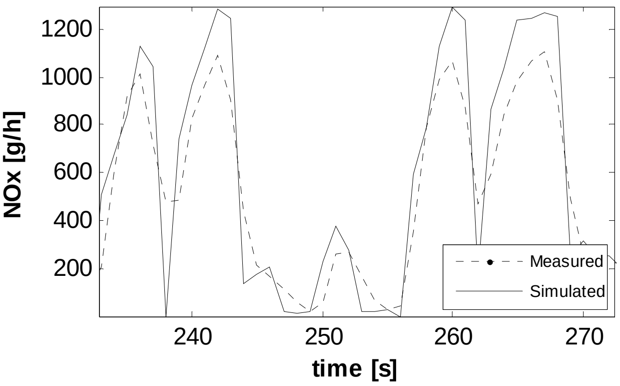

Figure 4 Measured and simulated QS NOx, engine B, sequence of the ETC

CO emissions are underestimated for all three engines. During steady operating conditions (for example 840-880 s), simulated and measured values correspond well (Figure 5). During transients however the measured peak in CO emissions is not predicted with the quasi stationary simulation.

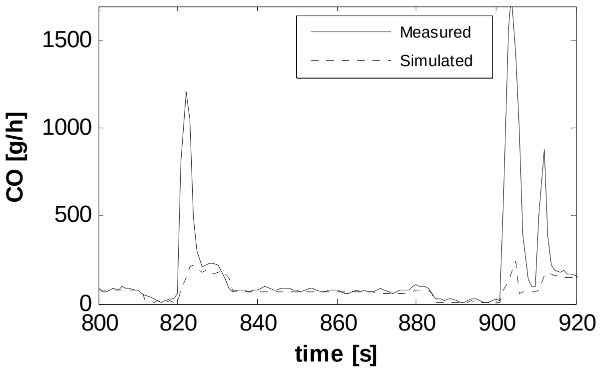

Figure 5 Measured and simulated QS CO, engine B, sequence of the TNO part3 test cycle

PM emissions are also underestimated. The difference is possibly related to transients, the slow dynamics of the TEOM measurements makes this identification difficult (Figure 6). Note that the TEOM instrument indicates negative values in some cases which of course isn’t physically possible. For both CO and PM emissions transient correction is essential. HC emissions are overestimated for all engines and must also be corrected.

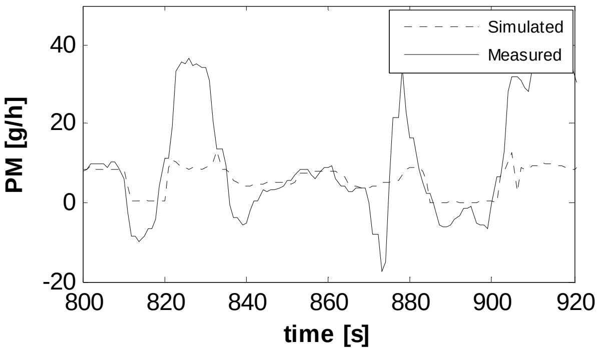

Figure 6 Measured and simulated QS PM, engine B, sequence of the ETC

THE DELAY MODEL

During the onset of a (positive) load transient the global lambda value will be lower for a given operating point compared to steady state conditions. As the transient decays, the lambda will be higher. The fuel injection system typically has a much faster response time than the turbocharger resulting in a delayed air mass flow compared to the fuel mass flow and thus a lower lambda during the onset of a transient and a higher lambda as the transient decays. The low lambda during the beginning of a transient will have a substantial effect on emissions. In heavy truck engines the fuel mass flow is restricted to a certain extent by the smoke limiter during transients (to avoid excessive soot), but the effect of turbocharger lag is still evident. The lambda predicted by the lambda map will differ from the measured value (Figure 7).

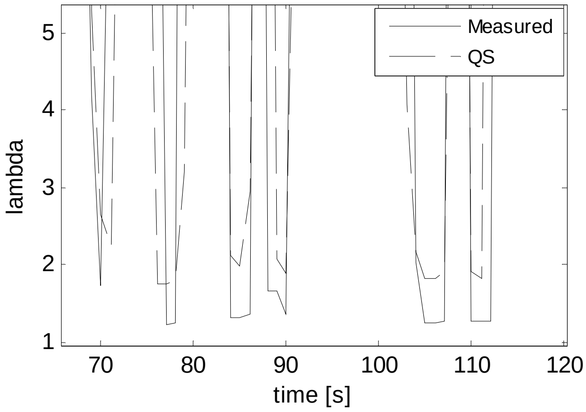

Figure 7 Measured and simulated QS lambda, engine B, sequence of the TNO part1 test cycle

One way of correcting the emissions values is based on the fact that (some of) the emission formation can be correlated to global lambda. It is a well known fact that CO emissions increase sharply below a break point (in this case λ~1.7) due to lack of oxygen during combustion. The trend is similar for all three engines (Figure 8).

Jiang et al. (3) uses similar CO/PM – lambda curves to simulate emissions, although emission flow values are used rather than Emission Index (EI) values (given in g emissions / kg fuel).

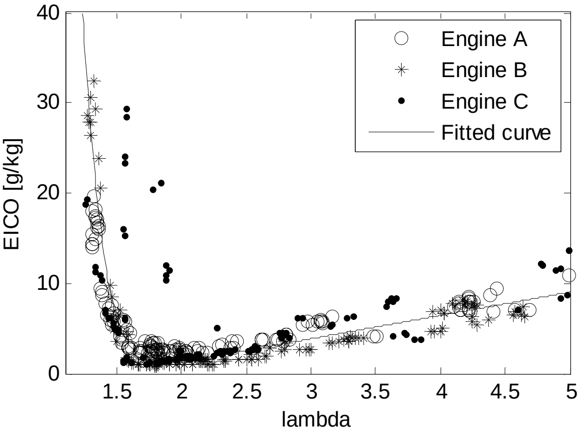

Figure 8 Measured EICO vs. lambda with fitted curve

An exponential function combined with a linear function is fitted to the steady state data in Figure 8:

$$EICO = \begin{cases} c_1 \cdot e^{-(\lambda + c_2)^4} + c_3 & \lambda \leq 2.2 \\ c_4 + c_5 \cdot \lambda & \lambda > 2.2 \end{cases} \tag{1}$$

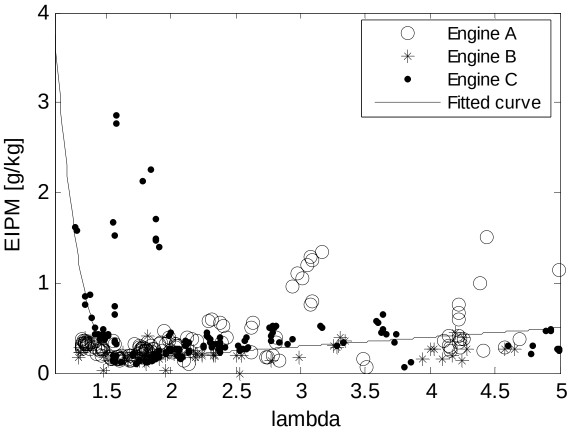

Figure 9 Measured EIPM vs. lambda with fitted curve

A similar trend with increasing values as lambda decreases can be shown for particulate emissions (Figure 9). This is related to lower oxygen concentrations making oxidation of particles less effective. Note that the results are not as consistent between the engines as is the case for CO emissions. Engine C shows a higher breaking point than Engine A and B. An average EIPM-curve was fitted to the data in order to get a general model:

$$EIPM = \begin{cases} c_1 \cdot e^{-(\lambda + c_2)^4} + c_3 & \lambda \leq 1.8 \\ c_4 + c_5 \cdot \lambda & \lambda > 1.8 \end{cases} \tag{2}$$

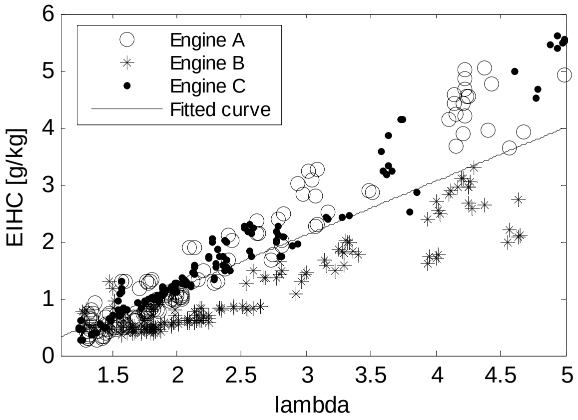

Figure 10 Measured EIHC vs. lambda with fitted curve

The HC emissions show a decreasing trend for decreasing lambda (Figure 10). Decreasing lambda results in a higher combustion/exhaust temperature and better oxidation of HC. A linear EIHC-curve is fitted:

$$EIHC = c_1 + c_2 \cdot \lambda \tag{3}$$

No similar relation between EINOx and lambda exists.

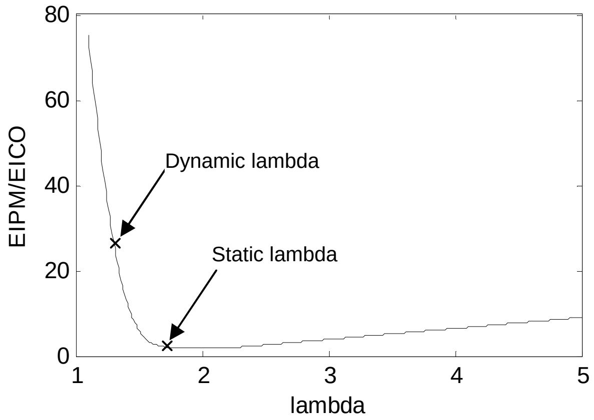

Figure 11 Illustration of dynamic and static lambda

The concept behind the delay model is to estimate a turbocharger delay time and calculate a corresponding transient/dynamic lambda in each time step. The dynamic lambda will differ (during transients) from the static lambda which is calculated from the lambda map. Using the emission index relations determined from steady state measurements EICO/PM/HC values corresponding to the dynamic and static lambdas is calculated (illustrated in Figure 11). In each time step the ratio between these two values is determined. This ratio is multiplied with the emission value determined from the emission map to get the transient corrected emission value.

For example using CO correction, the ratio is calculated:

$$CO_{corr} = \frac{EICO(\lambda_{dyn})}{EICO(\lambda_{QS})} \tag{4}$$

The quasi stationary value is multiplied with the CO-ratio to get the transiently corrected CO mass flow:

$$\dot{m}_{CO,corr} = \dot{m}_{CO,QS} \cdot CO_{corr} \tag{5}$$

In order to simplify the model, the assumption that the fuel system has a negligible response time compared to the turbocharger is made. The first step is to calculate a set of ideal delay times using measured emissions:

$$CO_{corr} = \frac{c_1 \cdot e^{-(\lambda_{dyn}+c_2)^4} + c_3}{c_1 \cdot e^{-(\lambda_{QS}+c_2)^4} + c_3} \qquad \lambda_{dyn}, \lambda_{QS} \leq 2.2 \tag{6}$$

$$\lambda_{dyn} = \frac{\dot{m}_{air}(t-\tau)}{14.7 \cdot \dot{m}_{fuel}(t)} \tag{7}$$

A Matlab program is used to increase the value of τ in increments from 0 up to a maximum of 2 seconds. After each increase in τ, the program checks if the calculated CO-ratio is closer to the measured ratio than the previous. Correction is only performed during the onset of a transient (positive delay times). The effect of overestimating lambda as the transient decays is negligible.

Using measured emissions for calculating delay times defeats the purpose of the model however. The delay times in this application must be predicted using only torque and speed as inputs. Regression analysis shows that the delay time is most strongly correlated to torque (M) and torque differential (dM/dt). Two different black-box model structures have been used:

$$\tau = k_1 + k_2 \cdot M + k_3 \cdot \frac{\partial M}{dt} \qquad , \lambda_{QS} \leq 2.2 \tag{8}$$

$$\tau = k_1 \cdot \left(1 - k_2 \cdot \frac{M}{\max(M)}\right) \cdot \frac{\partial M}{dt} \qquad , \lambda_{QS} \leq 2.2 \tag{9}$$

The second equation is based on the observation that the delay time will be greater for a given torque differential if the torque before the transient is low. The first polynomial model yields the best results and will be used from now on.

The TEOM particulate measurements are not suitable for generating ideal delay times because of the slow dynamics. It is assumed that the delay time model with parameters set using CO measurement data is valid for PM and HC correction as well.

RESULTS

The parameters in the delay model were optimized using a least-square fit. The results are shown in Table 2.

Delay time estimation (eq. 8)				
k_1	k_2	k_3		
0.234	6.26·10^-4	4.19·10^-5		
CO compensation (eq. 1)				
c_1	c_2	c_3	c_4	c_5
200	-0.10	1.80	-3.86	2.57
PM compensation (eq. 2)				
c_1	c_2	c_3	c_4	c_5
14.0	-0.020	0.170	0.103	-0.016
HC compensation (eq. 3)				
c_1	c_2			
-0.714	0.943			

Table 2 Optimized parameters, general delay model

The ratio of simulated over measured PM and CO emissions is improved with compensation (Table 3). Note that the compensation of PM emissions is less successful for engine C than for engine A and B. Transient correction of hydrocarbons based on the delay model is not adequate, the turbo lag is probably only one of several reasons for the over estimation.

	PM	**CO**	**HC**
Engine A	1,07 (0,70)	0,95 (0,59)	1,53 (1,58)
Engine B	0,98 (0,45)	0,99 (0,35)	1,40 (1,48)
Engine C	0,76 (0,48)	0,99 (0,53)	1,32 (1,36)

Table 3 Accumulated ratio simulated/measured after transient correction (ratio before correction within brackets)

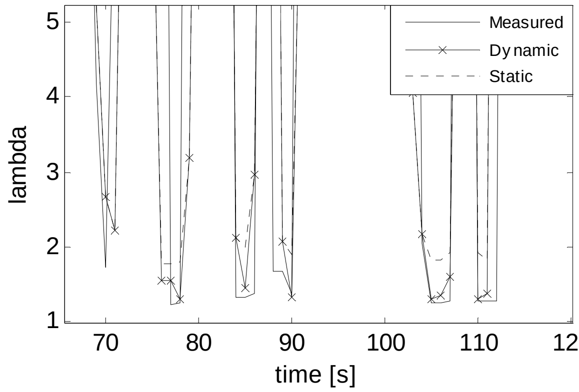

Figure 12 Measured, dynamic and static lambda, engine B, sequence of the TNO part1 test cycle

The dynamic (compensated) lambda is a better fit to measured values than the static lambda, indicating that the turbo lag delay concept is valid (Figure 12).

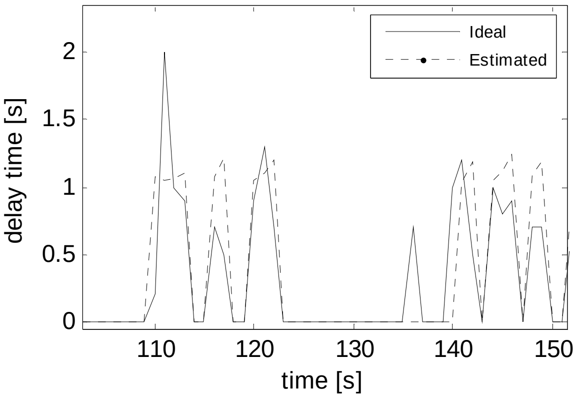

Figure 13 Ideal and estimated delay times, engine B, sequence of the ETC

The delay time estimation has some limitations, some transients are overestimated whereas some are underestimated (Figure 13). The mean absolute error is 0.22s for Engine B during the ETC cycle.

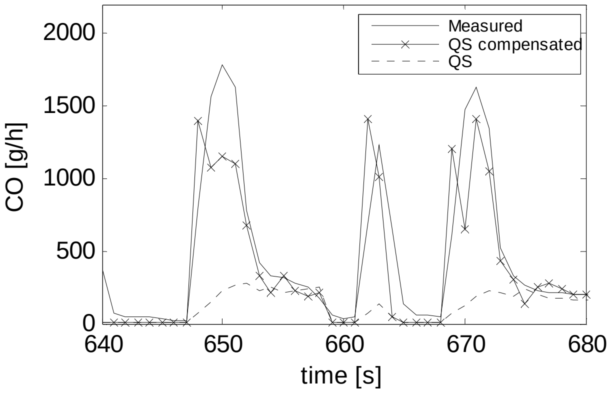

Figure 14 Measured and QS CO before and after transient correction, engine B, sequence of the ETC

Time resolved values for CO show that the delay model gives reasonable results (Figure 14). Using ideal delay times, nearly perfect results can be achieved (Figure 15). This is an indication that a better model for estimating the delay times would provide better overall results. The deviations in some transients are larger than what is desired in engine control (Figure 14).

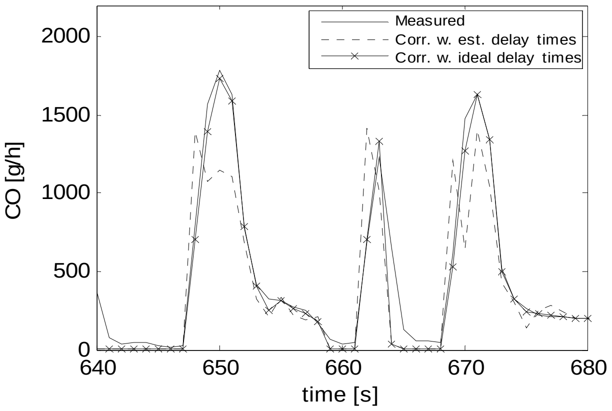

Figure 15 Comparison between CO emissions using ideal and estimated delay times, engine B, sequence of the ETC cycle

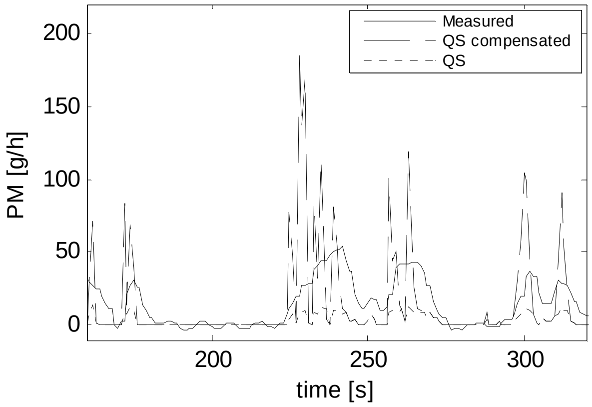

Figure 16 Measured and QS PM before and after transient correction, engine A, sequence of the ETC

The results of the transient correction of particulate emissions are shown in Figure 16. Although the accumulated results are excellent (Table 3), it appears as if the correction model over estimates PM in some points. One explanation for this could be the slow dynamics of the TEOM measurements; it is therefore not relevant to use the TEOM values to validate the correction model. It does however indicate that the transients are "in the correct places". By low pass filtering the transiently corrected PM, a good fit to the TEOM values can be achieved. This is not sufficient as a time resolved validation however.

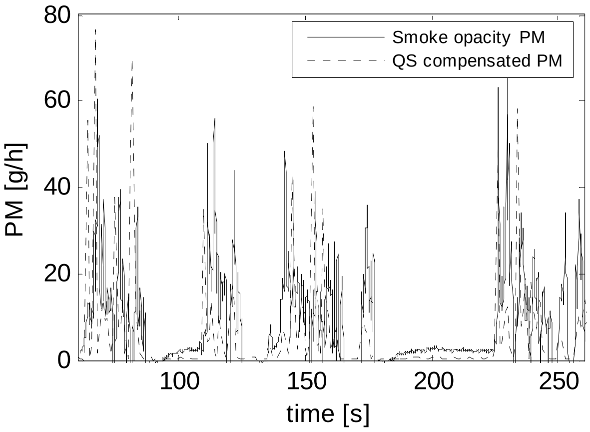

Figure 17 Smoke opacity-PM and transiently corrected QS PM, engine A, sequence of the ETC

Using smoke opacity values, a rough estimation of the particulate emissions can be calculated with empirical methods (5). A comparison between PM emissions calculated with this method and the transiently corrected QS PM values are shown in Figure 17. Note that the opacity measurements are from engine D and the QS values from engine A. Despite this fact it is interesting to note the similarity in transient properties, indicating that the highly transient character of the particulate levels calculated using the delay model is closer to the actual emissions than the TEOM measurements.

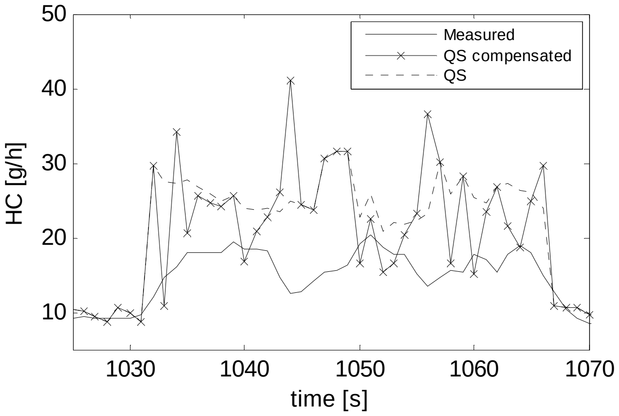

Figure 18 Measured and QS HC before and after transient correction, engine B, sequence of the ETC

The results of the transient correction of HC emissions are shown in Figure 18. The results are as disappointing time resolved as accumulated (Table 3). More mechanisms than turbo lag are responsible for the over estimation of HC emissions.

GENERALITY

The particulate transient correction of engine C is not as successful as that of engine A and B (Table 3). Better results can be achieved by fitting an individual EIPM-lambda curve to each engine. By using an EIPM-curve with a higher breaking point, optimized to engine C (Table 4), the average PM ratio over the four transient cycles is 1.01 for engine C compared to 0.76 with the general model.

PM compensation (eq. 2)				
c_1	c_2	c_3	c_4	c_5
20.0	-0.100	0.170	0.180	-0.149

Table 4 Optimized parameters, specific for engine C

Results for the individual cycles are shown in Figure 19. Some dispersion around the ideal value occurs, but the results are within 15% for all cycles compared to 30% with the general correction model. Slightly better results can also be achieved for engine A and B with individual EIPM-lambda relations.

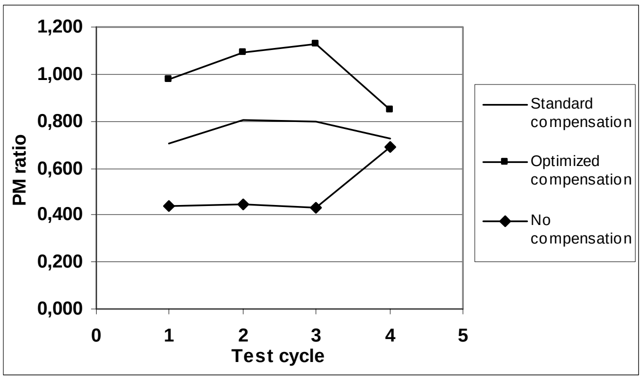

Figure 19 Comparison between standard and optimized PM compensation, engine C

The general CO correction model works well over all transient cycles (Figure 20) and further improvements are not motivated in this context.

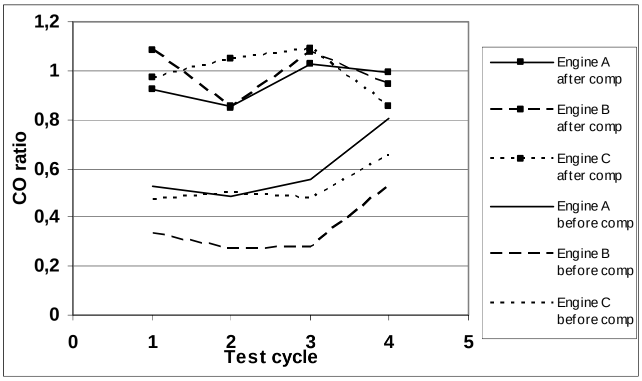

Figure 20 CO ratio before and after transient correction, engine A, B, C

By using optimization software to optimize the EI-curves and the delay time model (all in one step) to get best possible fitting to measured emissions, even better results can be achieved.

This method of setting the parameters does however defeat some of the physical interpretation of the delay model.

The engine maps differs between the engines studied, using the maps from engine A to predict the emissions from engine B and C offers poor performance (Table 5). The fuel consumption and NOx maps are fairly consistent for all engines, but using the CO and PM maps from engine A on engine B and C gives unacceptable results. The numbers in Table 5 are after transient correction with the general delay model.

	Fuel consumption	**NOx**	**CO**	**PM**	**HC**
Engine A	0,98 (0,98)	0,92 (0,92)	0,93 (0,93)	1,14 (1,14)	1,31 (1,31)
Engine B	0,94 (0,99)	1,18 (1,11)	0,26 (1,08)	0,30 (1,16)	1,13 (1,31)
Engine C	1,06 (1,02)	0,84 (0,77)	0,48 (0,98)	0,30 (0,75)	0,84 (1,27)

Table 5 Accumulated ratio simulated/measured values using engine A maps (ratio using individual maps within brackets), ETC cycle

The type of fuel used has an effect on performance; the ratios of measured emissions/fuel consumption using TUG/AVL reference fuel over EC1 fuel for engine C are shown in Figure 21. Fuel consumption and NOx emissions do not differ more than the typical measurement precision. PM and CO emissions vary more significantly; the TUG fuel generates higher emissions. The HC emissions are up to 70% higher using the TUG fuel than EC1 fuel. Compared to the typical 30-40% error generated by QS simulations this is quite significant. Considering that different fuel qualities are used over the world, this is an important factor to consider when estimating emissions from a large group of vehicles in real world conditions.

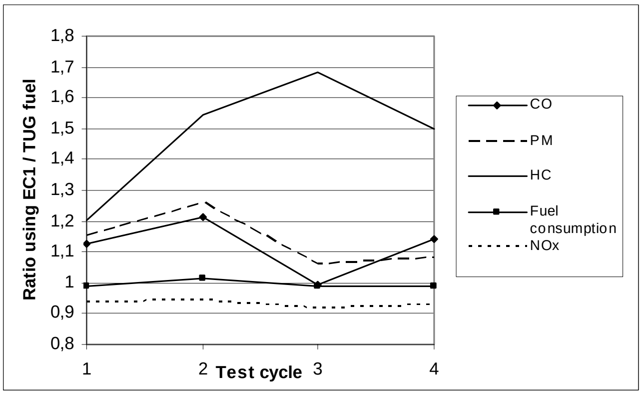

Figure 21 Comparison EC1/TUG fuel, engine C

CONCLUSION

The influence of transients on emissions and fuel consumption has been investigated. The difference between measured and quasi stationary CO and PM emissions has been identified to be caused by air shortage during transients because of the turbocharger lag. A successful time resolved delay time correction model has been developed which captures the behaviour and is able to correct the quasi stationary values. CO is typically predicted within 10% during all test cycles, and PM within 20%. NOx emissions are inconsistently over/underestimated by the studied engines as a result of active/dynamic control of injection timing, therefore no general correction model is possible. HC emissions are over estimated during transients. Some success applying the delay model to HC is achieved, although more work is needed. Fuel consumption is well predicted without correction models.

Differences exist between the studied engines although all three are of the same emissions classification. Better results can be achieved with a PM correction model fitted to each individual engine. The engine maps also differ substantially, making it questionable to use a common “Euro 3 CO map” for example. The fuel used has an influence on particularly HC, PM and CO emissions, differences up to 70% depending on the fuel used are observed. To get the best possible results, the correction models and engine maps should be classified not only according to emission rating but possibly also in sub-classes of technology used and fuel type. The technology sub-classes will be more obvious with Euro 4 engines where some manufacturers use EGR and others SCR.

The application of quasi stationary models (with correction functions) to engine control needs more work, especially the delay time estimation should be improved to get more consistent results.

ACKNOWLEDGMENTS

This work was partly financed by the Emission Research Programme (EMFO). The authors also would like to thank the COST 346 project for supplying measurement data and Ulf Hammarström, VTI in specific. AndersHedbom, AVL/MTC was helpful for his support on measurement details.

REFERENCES

1. Hausberger, S. Ivanisin, M. Riemarsma, I.J., “Modelling of transient influences on HDV emissions”, SAE_NA 2001-01-076, 2001
2. Hausberger, S., ”Simulation of Real Wolrd Vehicle Exhaust Emissions”, Postdoctoral thesis Technical University Graz, 2002
3. Jiang, Q. Van Gerpen, J. H., ”Prediction of Diesel Engine Particulate Emission During Transient Cycles”, Reducing Emissions from Diesel Combustion (SP895), 1992
4. Vora, K.A. Clark, N.N. et al., ” Correlation Study of PM and NOx for Heavy-Duty Vehicles Across Multiple Drive Schedules”, Emission Measurement and Testing, Advanced Catalysts and Substrates, and Diesel Gaseous Emissions (SP-1899), 2004
5. Homan, H.S., "Conversion Factors among Smoke Measurements", SAE 850267, 1985
6. Egnell, R., “Transient emission predictions for diesel engines with quasi stationary models”, The Swedish national road and transport research institute, VTI Notat 16A-2005, 2005

CONTACT

claes.ericson@scania.com

ABBREVIATIONS

EC1	Swedish diesel fuel
TEOM	Tapered Element Oscillating Microbalance
TNO	the Netherlands Organisation for Applied Scientific Research
TUG	Graz University of Technology
QS	Quasi Stationary