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## Summary

Current emission factors for PM10 for Euro-V trucks applied in national emission calculations are based on first estimates by experts and a few filter measurements in the laboratory. This situation stressed the need for actualisation based on measurements. It is generally known that PM and EC emissions are associated with high load, and transients power demand at high loads. So far, such measurement data has not been available, but an extensive test program, albeit on a single Euro-V SCR engine, made it possible to have separate filter measurement for different engine loads, for normal vehicle usage as defined by WHTC and ETC engine tests.

Hence, a first set of engine test-bed measurements on an Euro-V truck engine was performed by acquisition a comprehensive set of engine and engine emission data as input for the design of models and calculation of PM10 and EC emissions<sup>1</sup>.

Next, based on the performed engine test-bench measurements of especially the CO<sub>2</sub>, PM10 and EC emissions of the Euro-V truck engine, PM10 and EC emission models were designed and calibrated that allow the calculation of the instantaneous PM10 and EC emission rates from the instantaneous CO<sub>2</sub> emission rate. The CO<sub>2</sub> emission rate is directly related to the engine load of the vehicle. Hence linking PM and EC emissions to the instantaneous CO<sub>2</sub> rate, allows for a direct link between PM and EC emissions and the load profile of the engine.

By applying VERSIT+ to the TNO Standard Dutch HD Cycles for emission factor road types urban, rural and motorway, instantaneous CO<sub>2</sub> emission profiles were calculated for representative Euro-V truck types. Additionally, the new PM10 and EC models were applied to these CO<sub>2</sub> emission profiles to calculate the associated instantaneous PM10 and EC emission profiles and from these results the PM10 and EC emission factors were calculated.

After comparison of the newly derived HD Euro-V emission factors for PM10 and EC to the current estimated factors, it was judged that the new emission factors and the associated methodology are a credible and valuable update.

It is recommended that the new methodology is further evaluated and verified with engine test-bench measurements on additional Euro-V truck engine types. When such an evaluation and verification delivers good results it is recommended to expand the new methodology to other HD Euro emission classes as well.

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<sup>1</sup> PM10 refers to particulate matter with a particle size of less than or equal to 10 micron. Part of the particulate matter in vehicle exhaust consists of elemental carbon, commonly known as soot, and is designated as EC.

# Contents

	<b>Summary .....</b>	<b>2</b>
<b>1</b>	<b>Introduction.....</b>	<b>4</b>
<b>2</b>	<b>Engine Test-Bed Measurements on an Euro-V Truck Engine .....</b>	<b>5</b>
<b>3</b>	<b>Design and Calculation of PM10 and EC Models .....</b>	<b>8</b>
<b>4</b>	<b>Calculation of New PM10 and EC Emission Factors .....</b>	<b>12</b>
<b>5</b>	<b>Comparison of New and Current PM10 and EC Emission Factors .....</b>	<b>17</b>
<b>6</b>	<b>Conclusions and Recommendations .....</b>	<b>21</b>
<b>7</b>	<b>Signature .....</b>	<b>22</b>

## **Appendices**

A TNO Standard Dutch HD Cycles for Road Types Urban, Rural and Motorway

# 1 Introduction

With the introduction of DPF (diesel particulate filter) for diesel passenger cars from 2007, the particulate matter (PM) emissions of passenger cars are dropping rapidly, with 7% fewer diesel passenger cars without DPF every year. Hence, heavy-duty vehicles will be the dominant source of road traffic exhaust PM10 emissions the coming years. However with the introduction of Euro-VI, since September 2014, the DPF is standard also for heavy duty vehicles, and till 2020 the Euro-V vehicles become the dominant source of on-road exhaust PM10 emissions.

Current study is a comprehensive evaluation of the PM10 and EC emission<sup>2</sup> of a modern Euro-V engine equipped with SCR. A number of effects are studied: First, the effect of SCR technology on the PM10 emissions. Second, the effect of different road-types and driving behavior. Third, the effect of payload, or vehicle weight, on the emissions. This has led to a better differentiation with respect to vehicle type and road type of the PM10 and EC emissions of Euro-V heavy-duty vehicles. In particular heavy vehicles, with high engine loads, have higher PM10 and EC emissions.

The set-up of the experiment was the synchronous measurement of exhaust filter values, and on-line exhaust instruments, with repetitive cycles of exclusively urban, or rural, or motorway driving. These tests were engine tests, hence the actual engine load, expressed in the CO<sub>2</sub> emission rate had to be translated to the engine loads encountered on the road during the in-service conformity testing of Euro-V trucks.

With filter measurements, which are the standard method in both emission and air-quality measurements, the data is limited, hence a robust procedure was devised with three distinguished engine load operation regions, each with its own typical PM10 and EC emissions. PM10 emissions are dominated by high load while EC emissions have a slightly more even distribution over the different engine loads. The new analyses incorporates the engine dynamics, or transient emissions. Typically PM10 emissions are partly associated with high load conditions and partly with engine transients: changes in load. The emission factors combine these two effects by using real-world test cycles.

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<sup>2</sup> PM10 refers to particulate matter with a particle size of less than or equal to 10 micron. Part of the particulate matter in vehicle exhaust consists of elemental carbon, commonly known as soot, and is designated as EC.

## 2 Engine Test-Bed Measurements on an Euro-V Truck Engine

In order to obtain more realistic values for the PM10 and EC emissions of Euro-V trucks a comprehensive series of measurements was carried out on an single Euro-V truck engine in an engine measurement test-bed at TNO laboratories. This data is combined with the results of the on-road vehicle usage in the heavy-duty vehicles in the In-use compliance test program. The absolute levels comply with previous findings, however, the dependencies on payload and vehicle usage is matched against the engine power demand observed across the tested vehicles.

As PM10 and EC emissions are known to vary largely with varying engine loads, the engine was subjected to a series of internationally accepted test cycles as ETC and WHTC urban, rural and motorway. These cycles were repeated for better statistical significance and the entire measurement program took more than three days to complete. During execution of each test cycle a comprehensive set of engine and emission parameters was measured continuously with sample frequencies ranging from 5 Hz to once per minute. An example of a selected set of such measured signals is given in Figure 1. In Figure 2 it is illustrated that the instantaneous CO<sub>2</sub> emission rate and the engine power are directly and linearly proportional according to the so-called Willans line.

*In addition to the previously mentioned continuous measurements, exhaust particle filter measurements were performed giving total emission values of PM10 and EC for each executed test cycle. In Chapter 3 it will be explained how these PM10 and EC filter measurements per test were used together with the instantaneous CO<sub>2</sub> emission rate measurements to design and derive a model which relates the instantaneous CO<sub>2</sub> emission rate of an engine to its instantaneous PM10 and EC emission rates. The main reasons to try to design that type of model were the need for a model that predicts PM10 and EC emissions including variations due to driving dynamics and varying truck load and the idea that such a model should somehow include the actual demanded/delivered engine power during driving.*

Two types of particle related exhaust measurements were performed to see how these relate to the PM10 and EC filter measurements. These were 'black smoke' measurements with an AVL439 instrument (AVL for short) and 'black carbon' measurements with a Thermo Model 5012 MAAP instrument (MAAP for short). The AVL performs an optical opacity measurement of the exhaust and the MAAP a combination of optical absorption by black particles on a filter through which diluted exhaust is led and the weight of the particles caught per volume flow unit. The results for these two measurements will be reported elsewhere.

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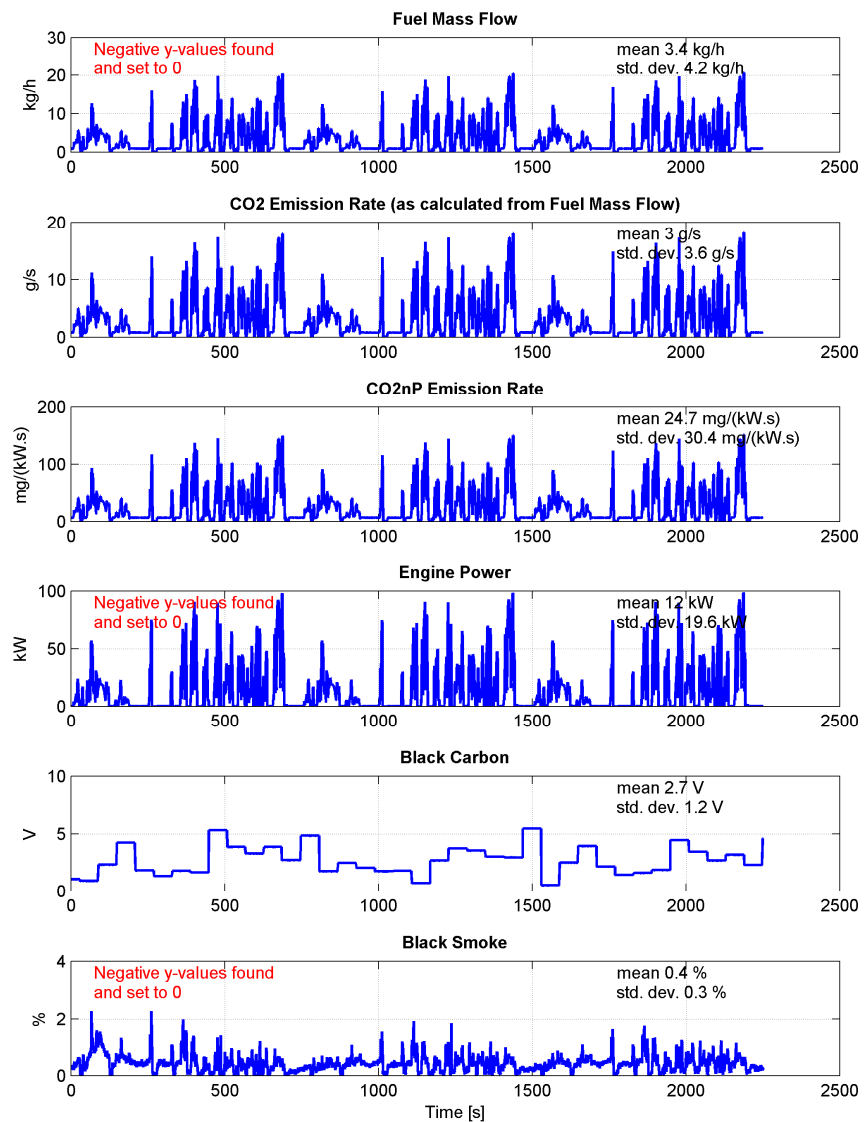


Figure 1 Example of measured signals for engine test-bed measurements on Euro-V truck engine during WHTC urban test cycle.

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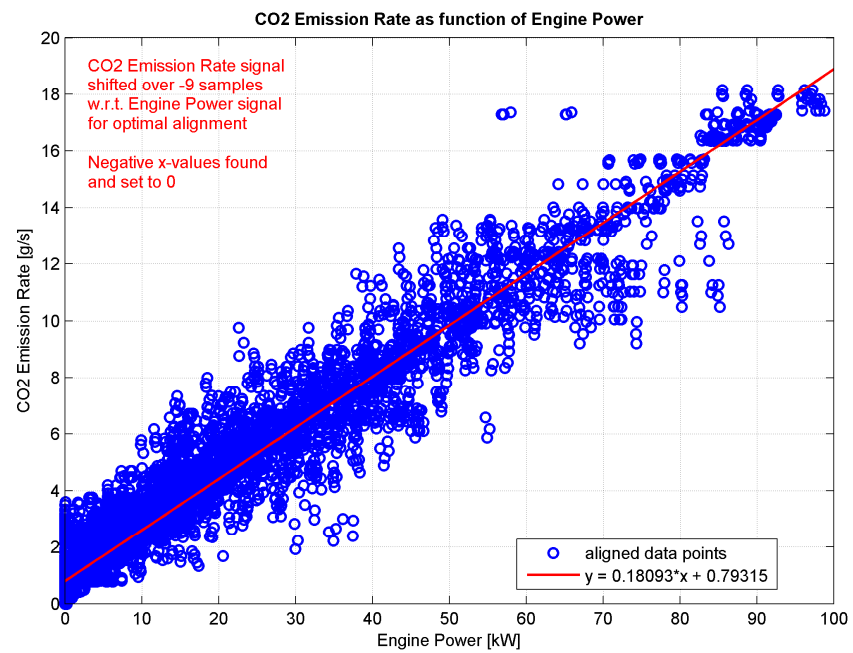
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Figure 2 Example scatter plot of CO<sub>2</sub> emission rate signal versus engine power signal clearly showing the 'Willans line' relationship between CO<sub>2</sub> emission and engine power.

### 3 Design and Calculation of PM10 and EC Models

The idea that a model for the prediction of PM10 and EC emissions of an engine should somehow include the actual demanded/delivered engine power originates from the awareness that engine power and fuel consumption, hence CO<sub>2</sub> emission, are directly and linearly related. And hence PM10 and EC must also be related to the CO<sub>2</sub> emission though, due to the complex and varying combustion conditions for varying engine loads, probably not in a simple linear fashion. Also, it was expected that the PM10 and EC emissions are varying with the driving dynamics that are typical for main road types such as urban and rural roads and motorways.

Hence, one of the relationships that were investigated in search of a model was the CO<sub>2</sub> emission as a function of the binned CO<sub>2</sub> emission rate normalised with the rated engine power<sup>3</sup> for each WHTC test sub cycle, i.e. urban, rural and motorway. This gives graphs as shown in Figure 3 to Figure 5. These clearly illustrate that the different road types, each with its own typical engine dynamics, give rise to characteristic patterns in the CO<sub>2</sub> emission as a function of the binned (rated power normalised) CO<sub>2</sub> emission rate. For PEMS CO<sub>2</sub> measurements on trucks in real-world driving tests similar patterns were observed (not shown in this report).

As the number of performed tests was limited<sup>4</sup>, the number of emission rate (ER) bins was reduced to only three (see example in Figure 6) and simple three coefficient emission models for the PM10 and EC emission rates of the following form were derived:

$$\text{PM10\_ER} = a_1 \cdot \text{CO2\_ER}_{\text{bin1}} + a_2 \cdot \text{CO2\_ER}_{\text{bin2}} + a_3 \cdot \text{CO2\_ER}_{\text{bin3}} \quad [1a]$$

$$\text{EC\_ER} = b_1 \cdot \text{CO2\_ER}_{\text{bin1}} + b_2 \cdot \text{CO2\_ER}_{\text{bin2}} + b_3 \cdot \text{CO2\_ER}_{\text{bin3}} \quad [1b]$$

The coefficients  $a_i$  and  $b_i$  are of course dimensionless. Specifying them in [mg/s]/[g/s] avoids small numbers. Note that CO<sub>2</sub>\_ER<sub>bin1</sub> means a CO<sub>2</sub> emission rate which value after normalization with the rated engine power falls in bin 1 and similarly for bin 2 and 3. The maximal CO<sub>2</sub> emission rate is proportional with the rated power. For a large heavy-duty engine one kW engine power would generate maximally about 0.18 g/s CO<sub>2</sub>. Hence 300 kW about 54g/s CO<sub>2</sub> at full engine load. In dynamic conditions the rate can be somewhat higher.

With the data as measured in the engine test-bed measurements, it appeared that the best bin borders, i.e. giving the best posterior predictions of the input data from which they were derived, were:

$$\text{bin}_1 \quad 0 < \text{CO2\_ER}/P_{\text{rated}} \leq 30 \quad \text{mg}/(\text{kW s}) \quad [2a]$$

$$\text{bin}_2 \quad 30 < \text{CO2\_ER}/P_{\text{rated}} \leq 90 \quad \text{mg}/(\text{kW s}) \quad [2b]$$

<sup>3</sup> This scaling with rated engine power was included to achieve that the same model may be applied to engines of different rated power.

<sup>4</sup> The ETC test cycle was performed 3 times but, ETC being rather stationary, the instantaneous CO<sub>2</sub> emission rate for it showed too small variation to cover the relevant CO<sub>2</sub>nP bin range as defined for the models. The 10 performed WHTC sub cycle tests were suitable in this respect. Thus, the number of usable test cycle tests used for the model coefficient calculations was 10.



$$\text{bin}_3 \quad 90 < \text{CO2\_ER/P\_rated} \leq 300 \text{ mg/(kW s)} \quad [2c]$$

Assuming all EC particles are smaller than 10 micron in size, the EC emission is always a fraction between 0 and 1 of the PM10 emission. Typically particulate matter particles from the exhaust are 10 -100 nm in size. Hence for the two emission rates should hold at any moment

$$\text{PM10\_ER} \geq \text{EC\_ER} \quad [3]$$

The PM10 and EC model coefficients  $a_i$  and  $b_i$  calculated from the measurement data, i.e. the binned instantaneous CO<sub>2</sub> emission rate data and the PM10 and EC filter values for the 10 tests, for the models given in equations [1a] and [1 b] are tabulated below.

Table 1 PM10 and EC model coefficients multiplied by  $10^3$ , i.e. effectively in [mg/s]/[g/s].

PM10		EC	
$a_1$	0	$b_1$	0.0227
$a_2$	0.0187	$b_2$	0.0058
$a_3$	0.0893	$b_3$	0.0143

Using the above coefficients in the model equations [1a] and [1b] it is obvious that, because the PM10 coefficient for the first bin is zero, the PM10 emission rate may become zero for certain low CO<sub>2</sub> emission rate values and hence smaller than the EC emission rate. This clearly needs improvement but for the time being was solved by adding the following extra constraint to the calculated PM10 emission rate values:

$$\text{PM10\_ER}(\text{PM10\_ER} \leq \text{EC\_ER}) = \text{EC\_ER} \quad [4]$$

Effectively, this constraint couples the two models in a physically defensible way and ensures the inequality in equation [3] is always obeyed.

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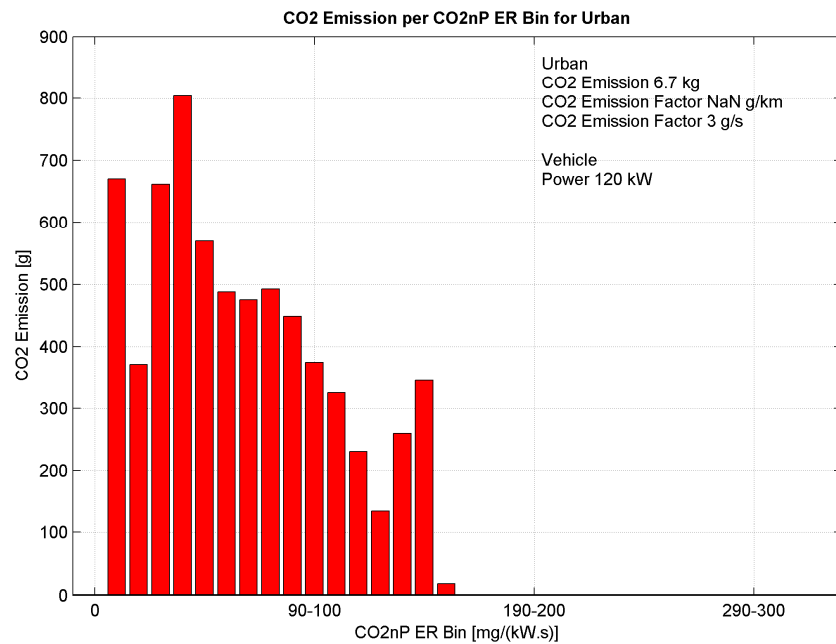
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Figure 3 Example of the CO<sub>2</sub> emission as a function of the binned CO<sub>2</sub> emission rate normalised with rated engine power for the WHTC **urban** test cycle.

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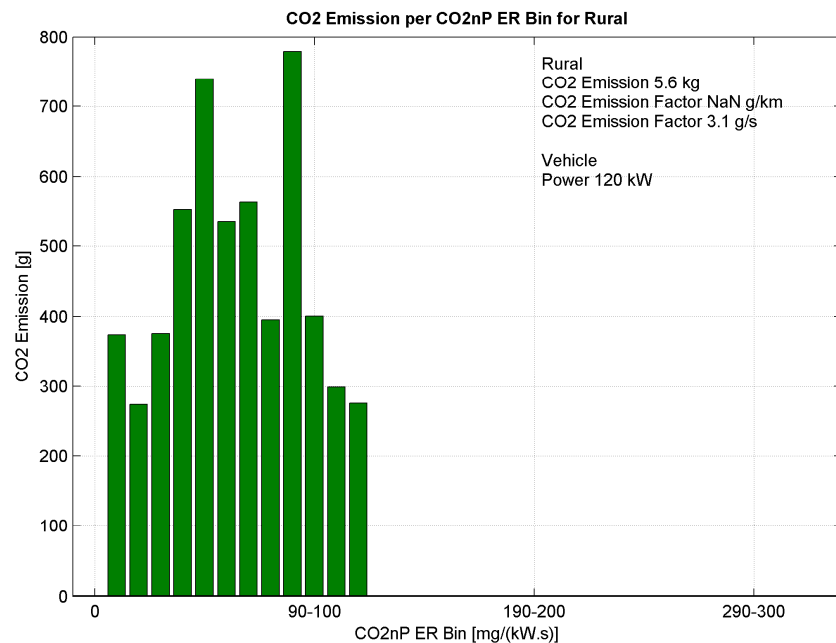
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Figure 4 Example of the CO<sub>2</sub> emission as a function of the binned CO<sub>2</sub> emission rate normalised with rated engine power for the WHTC **rural** test cycle.

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L558\_007\_M1\_5Hz\_CO2nP\_binned\_CO2\_Motorway.mat

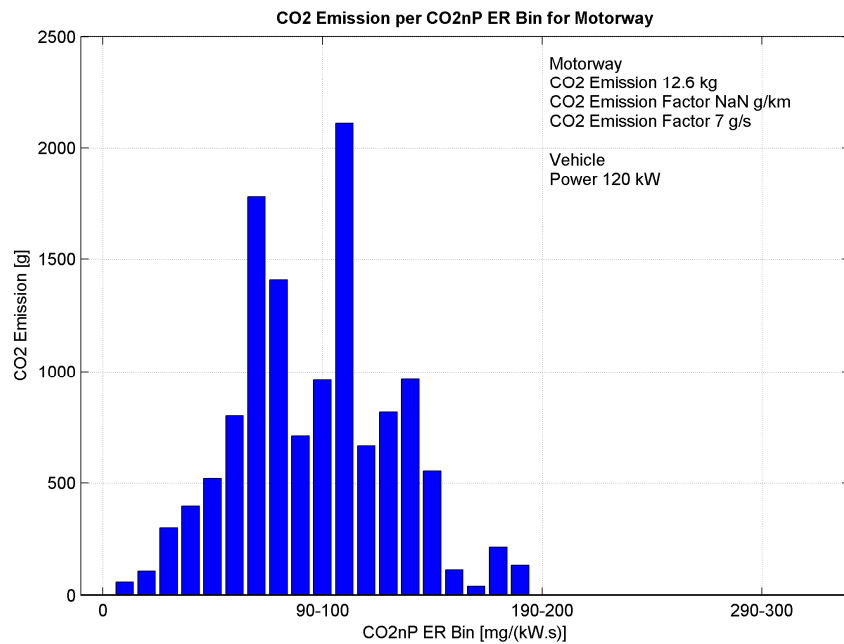
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Figure 5 Example of the CO<sub>2</sub> emission as a function of the binned CO<sub>2</sub> emission rate normalised with rated engine power for the WHTC **motorway** test cycle.

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L558\_005\_U1\_R1\_M1\_5Hz\_CO2nP\_binned\_CO2\_Total\_Trip.mat

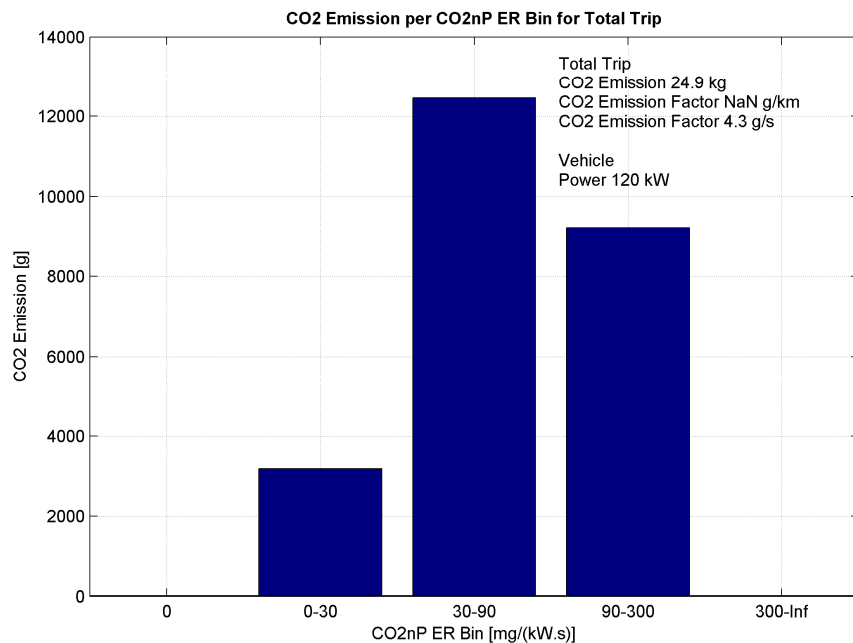
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Figure 6 Example of the CO<sub>2</sub> emission as a function of the binned CO<sub>2</sub> emission rate normalised with rated engine power for the **combined** WHTC **urban**, **rural** and **motorway** test cycles with three bins suitable for calculation of three coefficient models.

## 4 Calculation of New PM10 and EC Emission Factors

With the new PM10 and EC emission rate models available, the only thing missing for the calculation of new PM10 and EC emission factors is a set of representative CO<sub>2</sub> emission rate profiles for the truck and road types of interest.

With VERSIT+ such CO<sub>2</sub> emission rate profiles are readily calculated from representative sets of speed and associated acceleration profiles. Sometime ago TNO has derived from measurements a set of representative speed profiles for trucks for the road types urban, rural and motorway (WT1 to WT3), i.e. urban and rural roads and motorways. These speed profiles are the so-called TNO Standard Dutch HD cycles and graphs of these speed profiles together with the associated acceleration profiles of all of these have been included in Appendix A.

Thus, the procedure to calculate new PM10 and EC emission factors for a certain truck type for any of the three road types is as follows:

1. A combination of truck type and road type is selected.
2. With VERSIT+ the CO<sub>2</sub> emission rate profile for this combination is calculated from the appropriate speed and acceleration profiles.
3. Inserting this CO<sub>2</sub> emission rate profile into the new PM10 and EC models the corresponding PM10 and EC emission rate profiles follow.
4. Summing the emission rates and dividing by the trip length yields the new PM10 and EC emission factors.

In Figure 7 and Figure 8 this procedure is illustrated for a truck with VERSIT+ vehicle class ZVADEDE5SCRANH, i.e. a heavy truck with a trailer (ZVA & ANH) on diesel fuel (D) of Euro emission class V (EDE5) with selective catalytic reduction of NO<sub>x</sub> (SCR), on urban roads (WT1) as an example.

Repeating the procedure for a comprehensive set of 40 Euro-V truck types new PM10 and EC emission factors for all three road types were readily calculated. These have been depicted in Figure 9 to Figure 14. The graphs are grouped pairwise per road type, with each time the first in red for PM10 and the second in black for EC.

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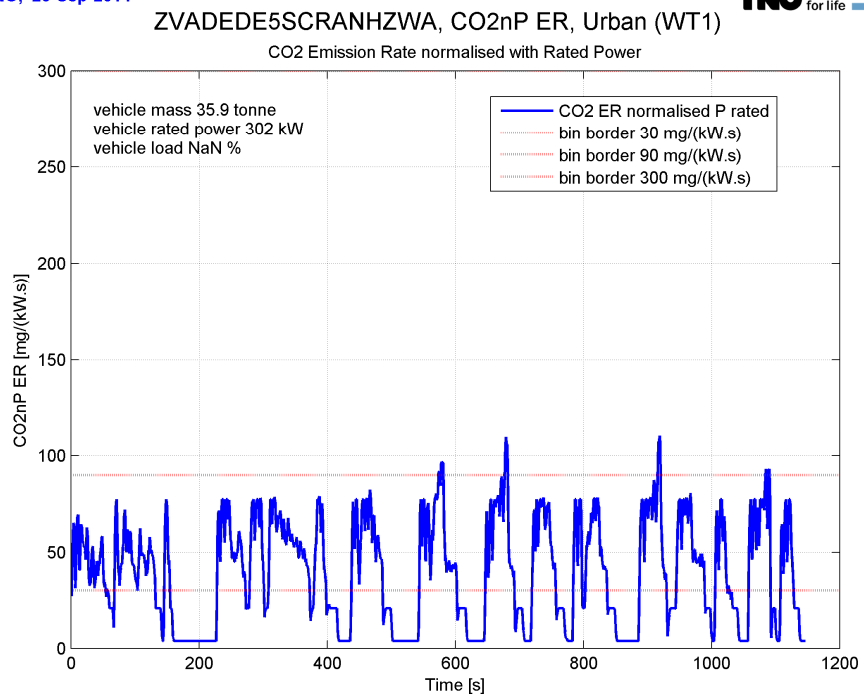
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Figure 7 Example of instantaneous CO<sub>2</sub> emission (here shown as CO<sub>2</sub>nP) as calculated with VERSIT+ for a truck with trailer on urban roads (WT1) with binning borders.

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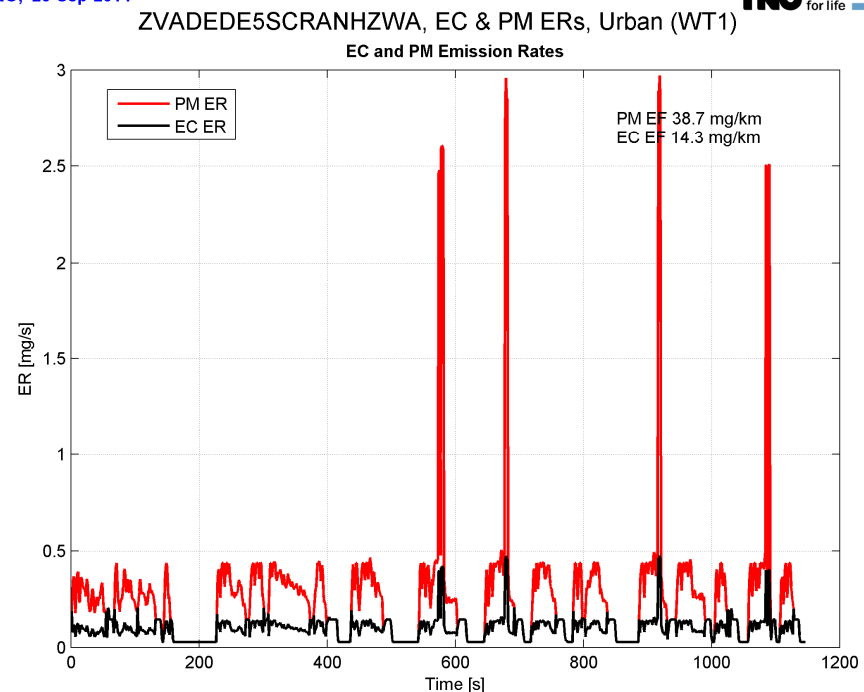
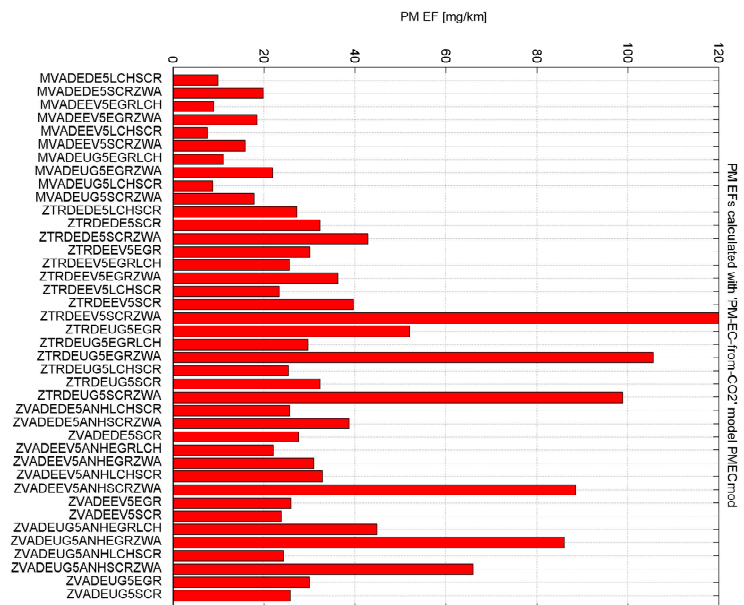
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Figure 8 Example of instantaneous PM (red) and EC (black) emissions as calculated from the above CO<sub>2</sub> emission rate profile with the new PMEC-from-CO<sub>2</sub> model.

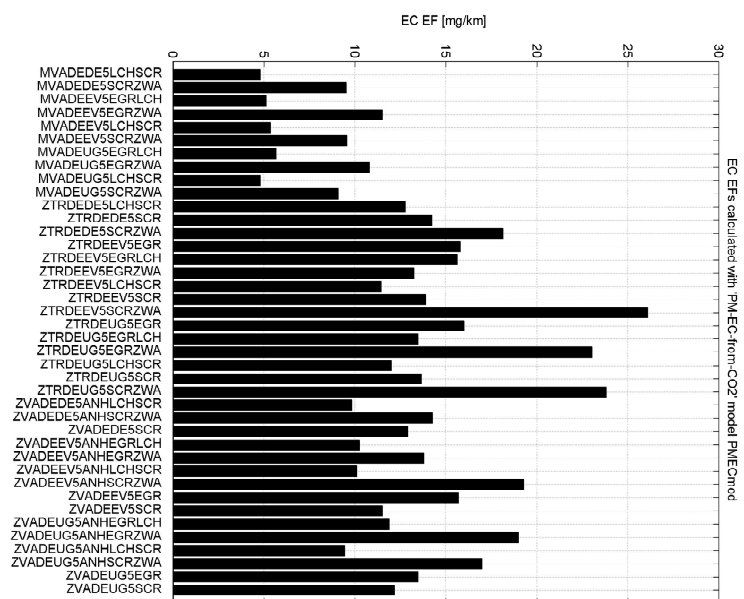


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HD Euro V, PMECmod PM EFs for WT1

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Figure 9 PM emission factors for Euro-V trucks on urban roads (WT1).

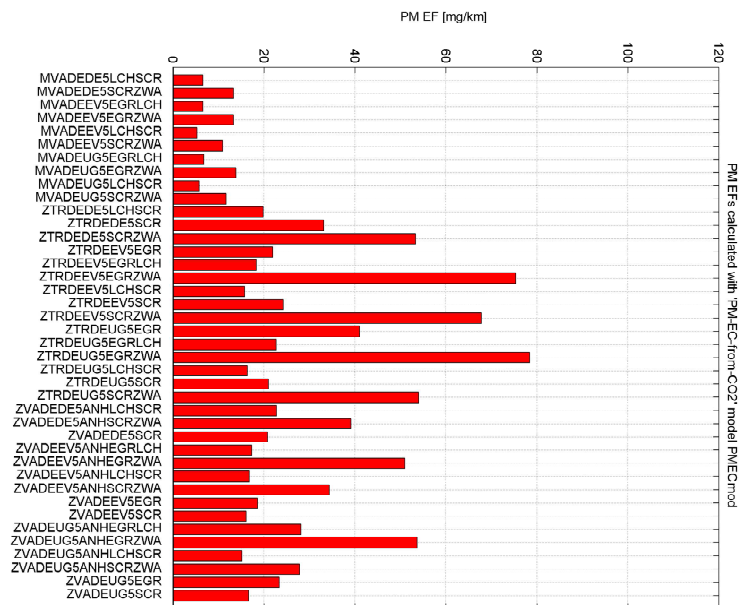


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Figure 10 EC emission factors for Euro-V trucks on urban roads (WT1).

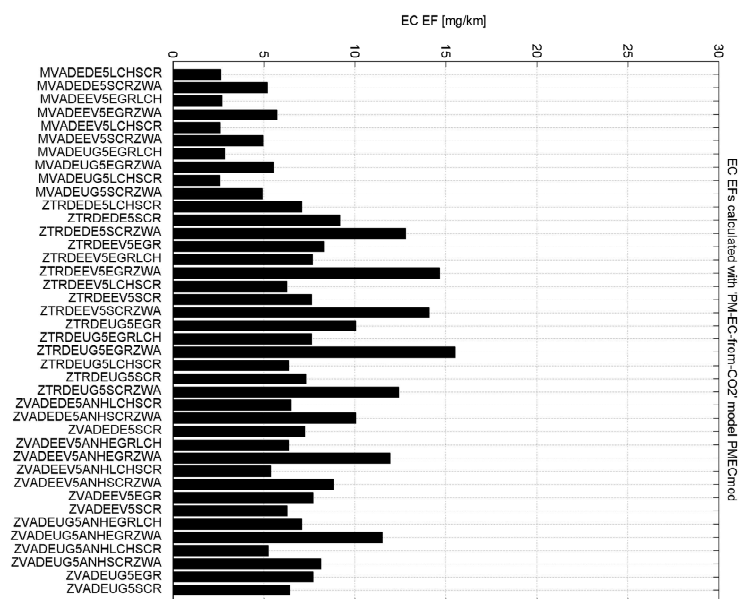


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Figure 11 PM emission factors for Euro-V trucks on rural roads (WT2).



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Figure 12 EC emission factors for Euro-V trucks on rural roads (WT2).

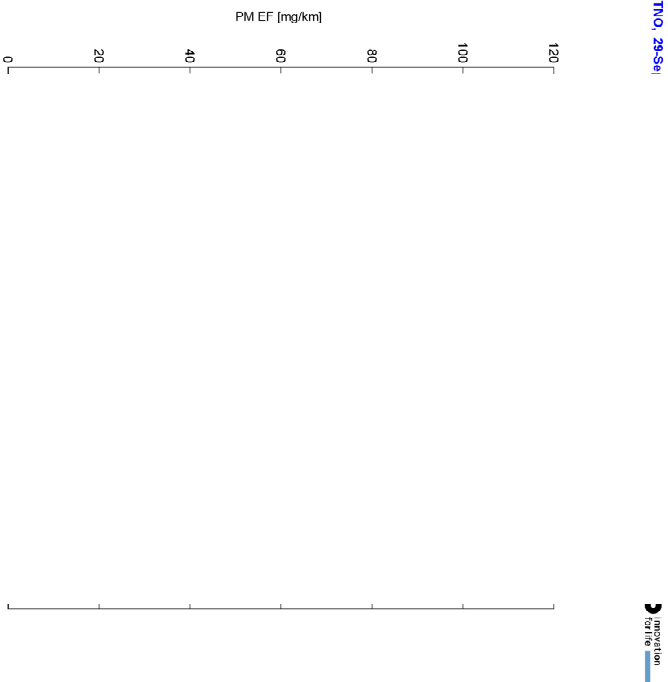


Figure 13 PM emission factors for Euro-V trucks on motorways (WT3).

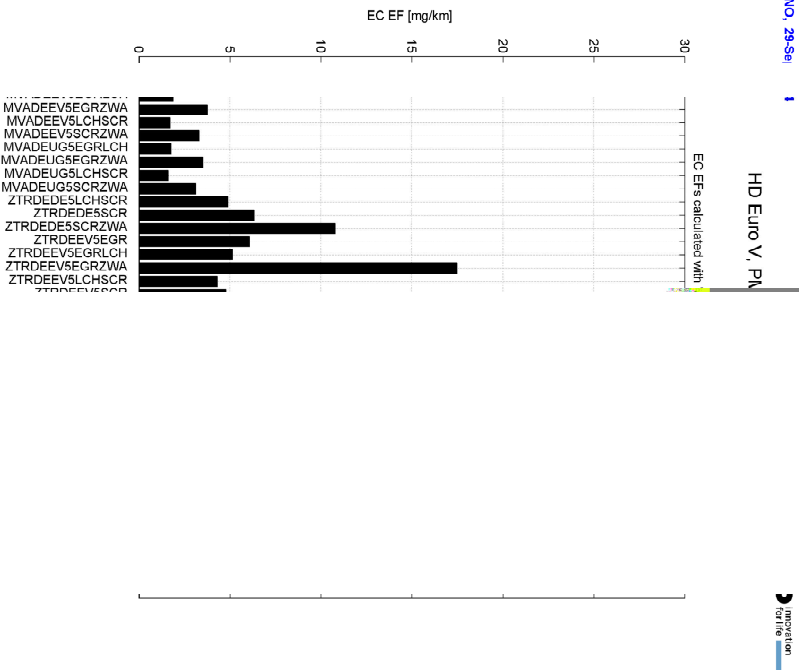


Figure 14 EC emission factors for Euro-V trucks on motorways (WT3).



## 5 Comparison of New and Current PM10 and EC Emission Factors

Now the new PM10 and EC emission factors have been calculated, it is interesting to compare these with currently applied emission factors. This was done using the PM10 and EC emission factors for Euro-V trucks from the current emission factor list<sup>5</sup>, i.e. "Detailmissiefactoren\_SRM\_20140212\_all.xlsx", and is shown in Figure 15 to Figure 20. As before the graphs have been grouped pairwise per road type and again the first plot, with data points depicted as red circles, is for PM and the second, with black circles, for EC. From these graphs the following observations are readily made.

First of all, for both emission factor types the order of magnitude of the new ones is quite comparable to that of the current ones.

For all three road types the new PM10 emission factors are usually lower than the current ones, i.e. the red circle data points lie below the green equality line, and sometimes higher. Furthermore the spread of the new PM10 emission factors is significantly larger than that of the current ones. For road type WT1, for example, the current PM10 emission factors all lie between about 20 and 60 mg/km, whereas the new ones spread considerably more from about 10 to 110 mg/km.

Engine tests provide emission standards for engines used in heavy-duty applications. For Euro-V the emission limit is 30 mg/kWh on a transient cycle. For a large tractor-trailer the power demand varies between 1 and 1.5 kWh per kilometre, such that in most cases, except for the vehicles with the smallest power-to-mass ratio (i.e., below 10 kW/ton) the on-road emissions are below the emission limit. This is related to the power demand in the ETC test, which is high compared to the real-world power demand.

For the EC emission factors the general picture is that all new EC emission factors are lower than the current ones, i.e. all black circle data points lie below the green equality line. The spread of the new EC emission factors is smaller (WT1) than or comparable (WT2,3) to the spread of the current ones.

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<sup>5</sup> It appeared that from the comprehensive set of 40 Euro-V truck types, for which new PM10 and EC emission were calculated, 21 Euro-V truck types are on the current SRM emission factor list.







## 6 Conclusions and Recommendations

Euro-V will be the dominant source of exhaust PM10 and EC emissions the coming years, as diesel passenger cars without filter are rapidly replaced by vehicles with filter (DPF). For heavy-duty vehicles the same transition is seven years later with Euro-VI (replacing Euro-V from September 2014) when DPF-filters become common. Detailed information of the PM10 emissions, and since recent years also the EC emissions, of the Euro-V vehicles is important for air quality assessments.

The current study addresses three subjects:

1. the typical PM10 and EC emission factors of a modern Euro-V engine equipped with SCR;
2. the dependency of PM10 and EC emission factors on road type: urban, rural and motorway;
3. and the dependency of PM10 and EC emission factors on payload, or power-to-mass ratio of the vehicles.

Compared with previous estimates of PM10 and EC emissions of Euro-V vehicles, the newly assessed emission factors are on average lower. However, the new emission factors of a group vehicles with a high power-to-mass ratio is higher. These are typically the larger trucks, with a high payload.

The study has a number of key ingredients, to ensure proper emission factors:

1. filter measurements on an engine test bench of separate urban, rural, and motorway driving;
2. repeated testing to ensure statistical significance;
3. the mapping of the engine load profiles as used on the engine test bench, to the load profiles as occur for heavy-duty vehicles on different road types with a variation in payloads.

These results are based on the extensive testing of a single modern Euro-V engine. However, the engine can be assumed to be representative of Euro-V engine technology, as the ETC values are similar to recovered from complete tests on other vehicles equipped with SCR. However, EGR technology, and variation with rated power, or engine size, cannot be study with this limited data.

The dependencies on payload and road type, which are difficult to analyse, as the PM10 and EC measurements have to be executed in the laboratory, are examined here extensively for the first time. Moreover, special care is taken to translate the outcome of filter tests on an engine test bench to the on-road engine load profiles as measured in the in-service conformity testing.

The dependence of PM10 and EC emission factors on road type and, in particular, vehicle payload is large. This has been known for a long time, from indicators like black smoke and opacity measurements. However, with this study the effect is properly quantified and attributed to the different aspects which determine the emissions, such as vehicle, payload, and road type.

## 7 Signature

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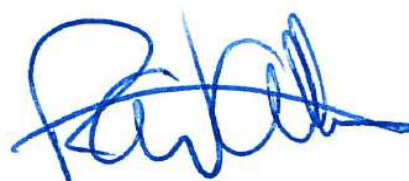
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Projectleader

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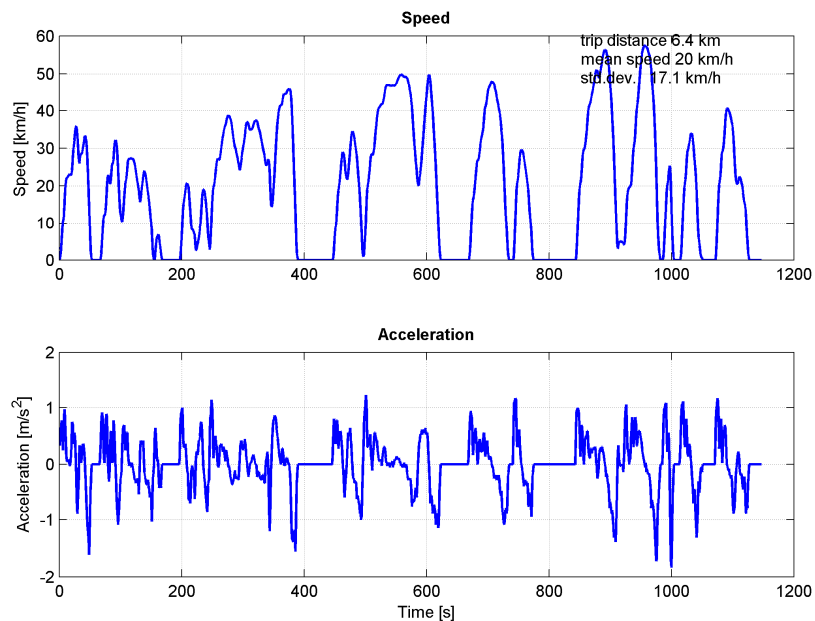


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## A TNO Standard Dutch HD Cycles for Road Types Urban, Rural and Motorway

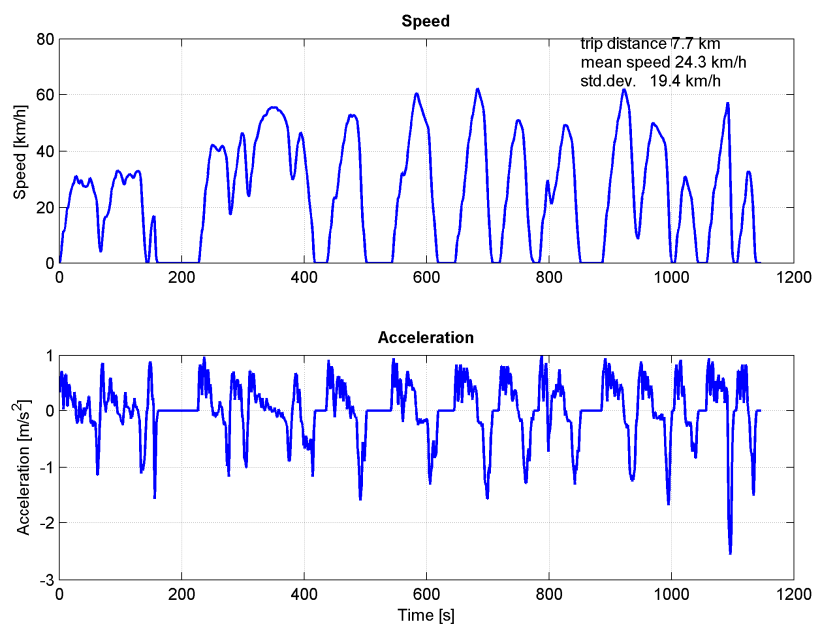
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TNO Dutch HD V-A-profiles, Truck, Urban (WT1)

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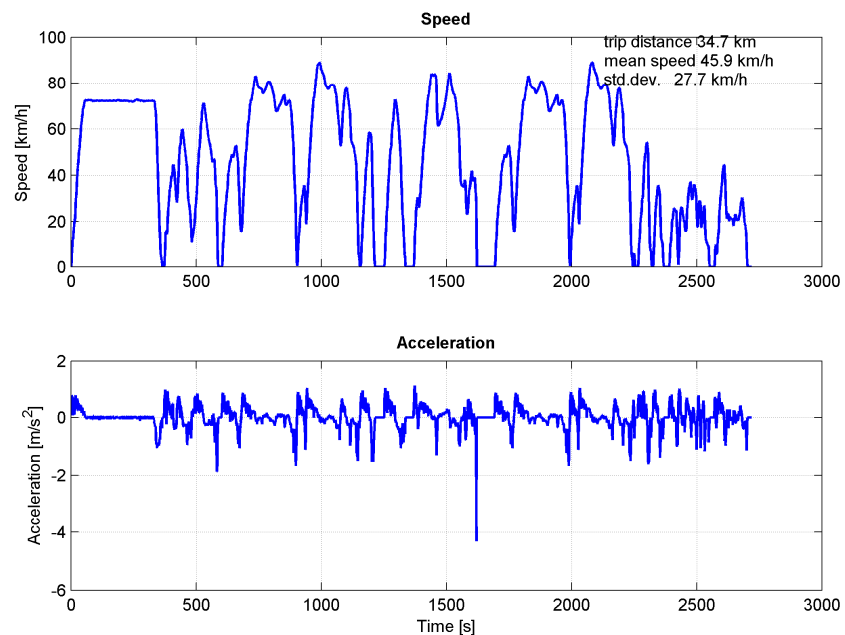
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TNO Dutch HD V-A-profiles, Truck with trailer, Urban (WT1)

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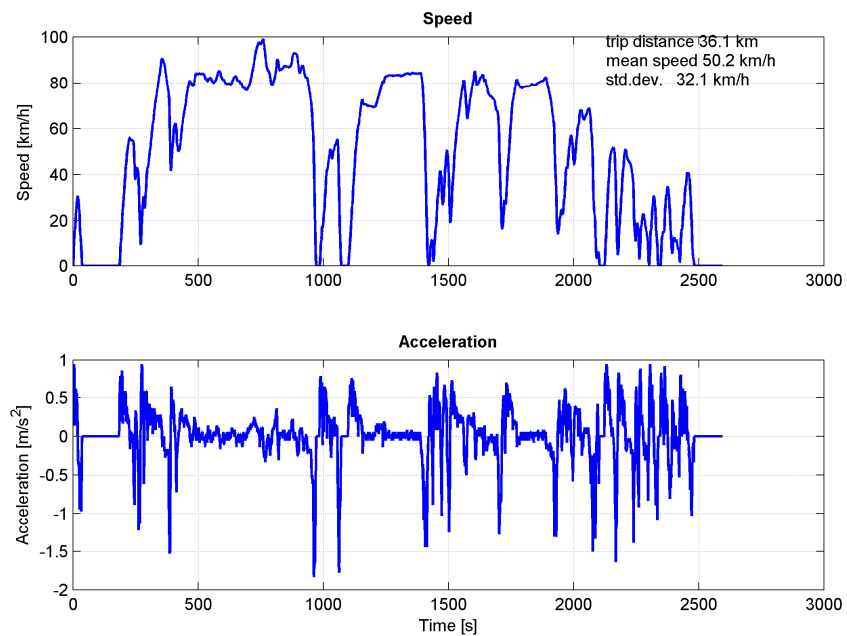
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## TNO Dutch HD V-A-profiles, Truck, Rural (WT2)

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for lifeFigure 23 TNO Standard Dutch HD Cycle: **Truck** on **rural** roads (WT2).

TNO, 23-Sep-2014

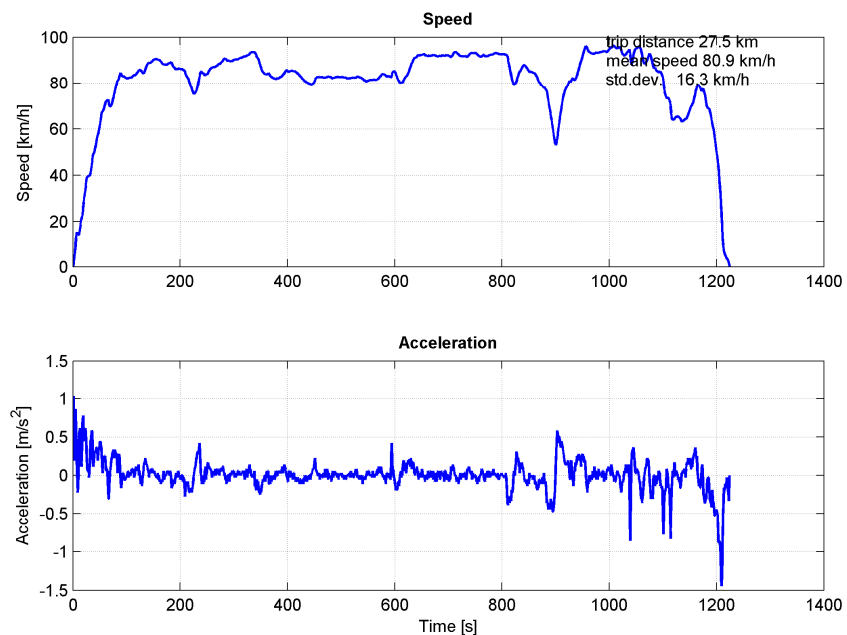
## TNO Dutch HD V-A-profiles, Truck with trailer, Rural (WT2)

TNO innovation  
for lifeFigure 24 TNO Standard Dutch HD Cycle: **Truck with trailer** on **rural** roads (WT2).



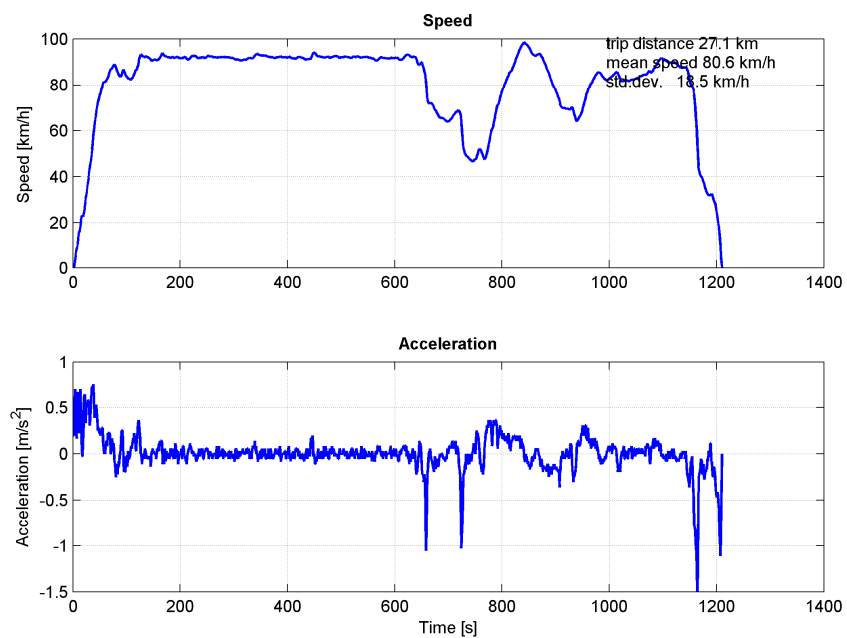
TNO, 23-Sep-2014

## TNO Dutch HD V-A-profiles, Truck, Motorway (WT3)

TNO innovation  
for lifeFigure 25 TNO Standard Dutch HD Cycle: **Truck** on **motorways** (WT3).

TNO, 23-Sep-2014

## TNO Dutch HD V-A-profiles, Truck with trailer, Motorway (WT3)

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for lifeFigure 26 TNO Standard Dutch HD Cycle: **Truck with trailer** on **motorways** (WT3).