



Technical feasibility of different regulatory OBD threshold limits (OTL) for Euro 6 (LD) vehicles

FINAL REPORT

**A study prepared for the European Commission
Directorate-General for Enterprise and Industry**

This study was carried out for the European Commission by



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TNO Report

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Technical feasibility of different regulatory OBD threshold limits (OTL) for Euro 6 (LD) vehicles - Final Report

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Summary

For on-board diagnostics (OBD) requirements in the Euro 6 Light Duty vehicle legislation, the detection of emission reduction system failures against the particulate OBD threshold limits (OTL) is of major importance. The OBD thresholds set out in Commission Regulation (EC) 692/2008 and amended by Commission Regulation (EC) 459/2012 are subject to a review to be conducted by the Commission by 1 September 2014. This report describes a study performed by a consortium of LAT, Ricardo UK and TNO, that aims to support the technical feasibility assessment of “Final OTLs” for particulate matter (PM) and NO_x for Euro 6 Light Duty diesel fuelled vehicles.

In the study worldwide OBD requirements, certification procedures, test methods and technologies introduced by OEMs on latest vehicle models with focus on PM and NO_x OTLs for Diesel vehicles were analysed. Further a desktop analysis to compare vehicle operation over the EU and US type approval driving cycles, in order to assess the relation between EU and worldwide OBD requirements was performed.

Summarizing all findings of this study, it can be concluded that:

- Besides the difference between US and EU legislation and type-approval procedures, the assessment revealed similarities in operation and OBD system performance and it was possible to draw a safe comparison path.
- Existing technologies allow the implementation of OBD hardware and algorithms able to cope with the more stringent Euro 6 PM and NO_x OBD requirements.
- Results were derived for vehicles belonging to the high engine capacity diesel engines in Europe.
- Cycle duration of the OBD demonstration type-approval cycle may be an issue for some vehicle manufacturers especially in the early stage of development. If deemed necessary the duration of the type-approval cycle may be extended to two consecutive non-stop driving cycles to allow more time for OBD monitor completion.

In continuation of this project it is proposed to:

- Keep track of rapidly developing OBD sensing hardware and monitoring technologies.
- Perform testing on more advanced systems in order to assess the possible need for extending the duration of the type-approval cycle to two consecutive non-stop driving cycles.

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1 Introduction

1.1 Background

On-Board Diagnostics, or OBD, in an automotive context, is a generic term referring to a vehicle's self-diagnostic and reporting capability. Commission Regulation (EC) 692/2008 for Euro 6 light duty vehicles (LDV), has a policy objective to align mandated OBD on a global level as much as possible.

Commission Regulation (EC) 459/2012/EC amends the Euro 6 LDV Regulation, including a set of OBD threshold limits (OTLs) applicable to Euro 6. The Regulation outlines Euro 6 OTLs in two steps. In the first step, the preliminary OTLs are introduced and will be applicable to passenger cars as from 1 September 2014.

The second step introduces (lower) "final" Euro 6 OBD threshold limits that are applicable to passenger cars as from 1 September 2017.

Regarding the introduction of these OTLs, the Regulation contains the following clause: "The OBD thresholds set out in the table are subject to a review to be conducted by the Commission by 1 September 2014. Where the thresholds appear to be not technically feasible, their values or the mandatory date of application are to be amended accordingly, considering the effects of other new requirements and tests that will be introduced for Euro 6 vehicles. Where the review shows an environmental need as well as technical feasibility and a net monetised benefit, more stringent values need to be adopted and OBD threshold limits for particle numbers or, where applicable, other regulated pollutants introduced. In doing so, appropriate lead time for introducing the technical developments has to be given to the industry."

In earlier work, the Commission Services and the Contractor have assessed the technical feasibility of different regulatory OTLs for Euro VI (HD) vehicles with a focus on PM and PN emissions, under specific contract SI2.609222. The necessary activities to complete such an assessment and comparable activities for Euro 6 (LD) vehicles were excluded from this work. Therefore a specific service request has been issued by the EC to follow up the activities for Euro 6 (LDV) OTLs, aiming at supporting the technical feasibility assessment of "Final OTLs" for PM and NO_x for Euro 6 Light Duty vehicles, as defined in Commission Regulation (EC) 692/2008 and amended by Commission Regulation (EC) 459/2012.

The specific service request has been issued by the EC under Framework Service Contract ENTR/09/030 "On-board diagnostics and other electronic or combined mechanical/electronic automotive systems". This contract, managed by TNO, aims to provide the Commission with the necessary information to support the legislative process and for the revision of clauses of current and upcoming OBD regulations where necessary. The work that is reported in this document has been performed by LAT, Ricardo UK and TNO.

1.2 Aim and approach

Objective of the reported work was to support the technical feasibility assessment of "Final Euro 6 OTLs" for PM and NO_x, as defined in Regulation (EC) 692/2008 as amended by Regulation (EC) 459/2012. As explained, the focus is on particulate matter (PM) and NO_x OTLs.

The work essentially focussed on providing the Commission with the necessary information in support of the legislative process and revision clauses of current and upcoming OBD regulations. In view of the fact that several vehicles with soot and NO_x sensors for OBD purposes have recently achieved certification in the US, it is clear that in principle sensor technology is technically capable of complying with the US OBD legislation.

The required assessment has therefore been to take this reality into account and to review the issues arising out of the use of the sensors in the US market and how these would impact introduction on to the EU market. The outcome of the work will further support the discussion on the transferability of PM and NO_x OTL detection technology applied in the US for EU OBD purposes in view of the applied type approval driving cycles. The work contained:

- An Investigation of US OBD requirements, certification procedures, test methods and technologies introduced by OEMs on latest vehicle models with focus on PM and NO_x OTLs for Diesel vehicles.
- A desktop analysis to compare vehicle operation over the EU and US type approval driving cycles, in order to assess the relation between EU and worldwide OBD requirements.

1.3 Structure of the report

This report presents the results of the work performed under specific contract SI2.659424.

Under section 2, this report includes the outcome of the review current worldwide OBD requirements, certification procedures, test methods and technologies introduced by OEMs on latest vehicle models with focus on PM and NO_x OTLs for Diesel vehicles.

Section 3 focusses the outcome of the desktop analysis to compare vehicle operation over the EU and US type approval driving cycles, in order to assess the relation between EU and worldwide OBD requirements.

Section 4 contains the discussion on the results that lead to the main conclusions and recommendations, in section 5 the conclusions and recommendations are reported.

2 Worldwide OBD requirements, certification procedures, test methods and technologies

In this chapter a review of current worldwide OBD requirements, certification procedures, test methods and technologies introduced by OEMs on latest diesel vehicle models is provided.

The focus of the review is on PM and NO_x OTLs with particular emphasis on US and European legislation.

2.1 Description of worldwide OBD type approval / certification procedures

In Section of 2.1.4 of the earlier work reported in Ref.[3], an overview of global Light-duty and Passenger car legislation is summarised. The corresponding global technical requirements for On-Board Diagnostic (OBD) systems for road vehicles tend generally to adopt or be derived from either US or European legislation. A representative sample of world markets is outlined below.

2.1.1 India OBD Requirements

Since the year 2000, India has adopted European emission regulations for four-wheeled light-duty and for heavy-duty vehicles.

A phased introduction of Euro 2 - 4 regulations is summarized in table below

| Standard | Reference | Year | OBD Requirements |
|------------------|-----------|-------------|-----------------------------------|
| Bharat Stage II | Euro 2 | 2001 – 2005 | |
| Bharat Stage III | Euro 3 | 2005 – 2010 | |
| Bharat Stage IV | Euro 4 | 2010 – | OBD I required from 1 April 2010 |
| | | | OBD II required from 1 April 2013 |

The OBD II is based on EOBD at Euro 4 level.

2.1.2 Brazil OBD Requirements

Brazilian passenger car emission regulations are specified in increasingly stringent stages, designated PROCONVE L-1, L-2, L-3, etc :

| Standard | Reference | Year | OBD Requirements |
|---|-----------|-------|---|
| PROCONVE L-4 | Euro 3 | 2007+ | |
| PROCONVE L-5 | Euro 4 | 2009+ | Br-1: 2010 Electrical continuity only Br-2: 2011 OBD II ⁽¹⁾ |
| PROCONVE L-6 | | 2014+ | |
| (1) Similar to Euro 4 EOBD – but using drive cycle FTP-75 | | | |

2.1.3 China OBD Requirements

Chinese Light-duty and Passenger car standards are based on European regulations. Vehicle classifications are also based on the EU classification with some minor changes:

- Type 1 vehicles: M1 vehicles for no more than 6 passengers including driver, and GVW \leq 2.5 ton.
- Type 2 vehicles: Light-duty vehicles (including N1 light commercial vehicles) further divided into three classes based on reference mass (RM).

| Standard | Reference | Year | OBD Requirements |
|----------|-----------|------|--|
| China 1 | Euro 1 | 2000 | |
| China 2 | Euro 2 | 2002 | |
| China 3 | Euro 3 | 2005 | European OBD introduced from December 2006 |
| China 4 | Euro 4 | 2008 | EOBD |
| China 5 | Euro 5 | 2013 | EOBD |

2.1.4 Russia Emission/OBD Standards

Russia adopts European emission standards for both manufactured and imported vehicles. Implementation dates are as indicated in the table below

| Standard | Reference | Year | OBD Requirements |
|----------|-----------|------|---------------------------|
| – | Euro 2 | 2006 | |
| – | Euro 3 | 2011 | |
| – | Euro 4 | 2014 | |
| – | Euro 5 | 2015 | As defined in Euro 5 EOBD |

2.1.5 South Africa Emission/OBD Standards

South Africa adopts European emission standards for both manufactured and imported vehicles.

Until recently Euro 2 was the effective level. However from 2012 the effective standard is Euro 4.

| Standard | Reference | Year | OBD Requirements |
|----------|-----------|------|--------------------------|
| – | Euro 2 | – | No OBD requirements |
| – | Euro 4 | 2012 | Corresponding EOBD level |

2.1.6 Japan OBD Standards

Japanese OBD II standards became effective from 2008 and are detailed in the Automobile Type Approval Handbook for Japanese Certification ("Blue Book") Section 11-3-48.

OBD threshold values are as listed below:

| Vehicle | CO (g/km) | NMHC (g/km) | NOx (g/km) |
|-----------------------------------|-----------|-------------|------------|
| Passenger and Light Duty Vehicles | 4.06 | 0.28 | 0.30 |
| Mini-sized Commercial Vehicles | 2.46 | 0.28 | 0.30 |
| Medium Duty Vehicles | 14.28 | 0.28 | 0.30 |

The test procedure for the above threshold values is a weighted combination of the JC08 cold test and the 10.15 mode test.

Note that the Japanese OBD legislation does not include thresholds for PM emissions.

2.1.7 Summary

Based on the sample above it is clear that in almost every case (apart from Japan), the OBD requirements are based on, and lag those in either Europe or the US. The map below summarises the global situation.

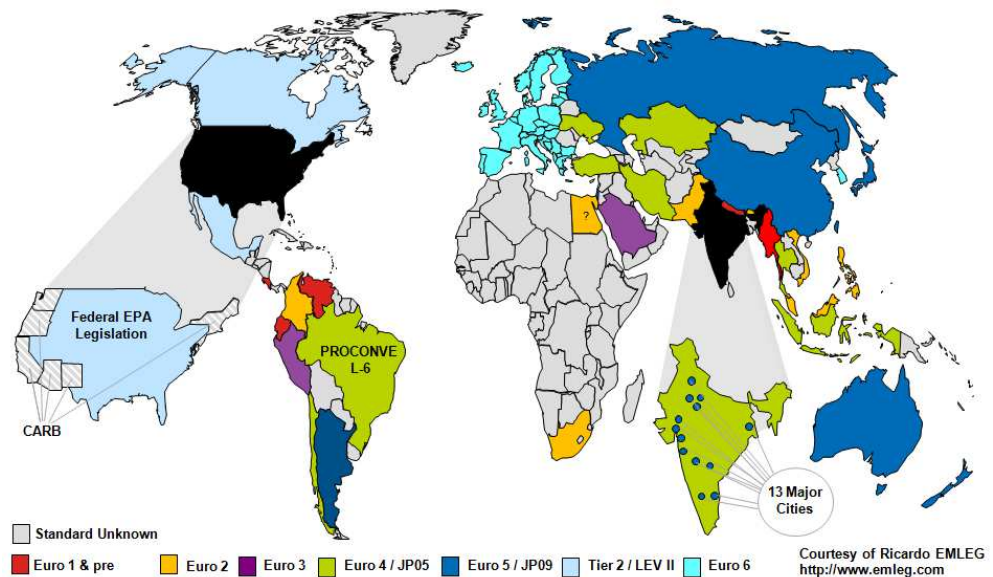


Figure 2.1: Summary of the global situation of OBD requirements

On the basis of the global situation as summarised in the above map, this report has focussed on a detailed review of the latest European and US OBD legislation as good representations of the future direction of worldwide OBD requirements.

2.2 Comparison of EU vs. US procedures

The United States Environmental Protection Agency (EPA) is the part of the US federal government authorized to draw up regulations necessary to implement US environmental laws. In terms of OBD requirements for light duty applications, the Federal OBD Requirements are outlined in Title 40 of the Code of Federal Regulations (CFR) Chapter I, Subchapter C, Part 86 Subpart S, Section 86 (Ref.[22]).

Within the State of California, the Air Resources Board (CARB) has the responsibility to draw up regulations necessary to reduce the emission of smog-forming pollutants and toxics from “mobile sources” in the state – which include sources such as passenger cars.

Due to the considerably severe environmental problems that pertain in parts of California (e.g. Los Angeles), CARB legislation has historically tended to be more stringent than that promulgated by the EPA federally.

As a result, demonstration of compliance with California OBD II requirements as detailed in Ref.[21], is deemed by EPA to satisfy the Federal OBD requirements as

detailed in Ref.[22]. This report will thus focus entirely on CARB OBD-II legislation in making a comparison between European and US OBD requirements.

Table 2.1: comparison between European and US OBD requirements

| CARB OBD-II (Ref.[21]) | Ref | Euro OBD (Ref.[1] & [23]) | Ref |
|--|----------|---|--------------------|
| OBD System must operate without maintenance for actual life of vehicle | (d)(1) | OBD System must operate over the entire life of the vehicle – but may show degraded monitoring performance due to ageing | [23] 3.1 |
| Monitoring conditions must be encountered in normal urban use, and must occur during the FTP cycle or Unified cycle | (d)(3) | Monitoring conditions must be encountered in “normal use”, and must occur during NEDC cycle. | [23] 3.2 |
| <u>Demonstration Test:</u> <ul style="list-style-type: none"> • Not witnessed by ARB • Use durability test vehicle, or a representative high mileage vehicle, or vehicle aged to end of full useful life using ARB-approved durability procedure | (h)(2.3) | <u>Demonstration Test:</u> <ul style="list-style-type: none"> • Witnessed by cert authority • Use durability test engine – or suitably aged and representative vehicle | [23] 3.3.1 |
| <u>Pre-conditioning:</u> <ul style="list-style-type: none"> • FTP, SET, or Unified Cycle • (+ 1 cycle identical to the initial preconditioning cycle, or a Federal Highway Fuel Economy Driving Cycle if required) • Manufacturer may not require test vehicle to be cold soaked prior to conducting preconditioning cycles | (h)(5.1) | <u>Pre-conditioning:</u> <ul style="list-style-type: none"> • Part 1 and 2 NEDC • (+ 2 Part 2's if required) • Alternative pre-condition cycle may be allowed if requested | [23] App.1 6.2.1 |
| <u>Test Sequence:</u> <ol style="list-style-type: none"> 1) Install faulty component (at the OTL) on the test vehicle (or simulated fault) 2) Carry out preconditioning 3) If required, a cold soak may be performed at this stage 4) Operate test vehicle over the applicable cycle to allow initial detection of the malfunction 5) Operate test vehicle over applicable emission test | (h)(5.2) | <u>Test Sequence:</u> <ol style="list-style-type: none"> 1) Install faulty component (at the OTL) on the test vehicle (or simulated fault) 2) Carry out preconditioning 3) Operate test vehicle with a simulated malfunction over NEDC test cycle and measure emissions (Manufacturer may request that monitoring take place outside the NEDC test cycle) | [23] App.1 (2) |
| <u>Evaluation Protocol:</u> <ul style="list-style-type: none"> • MIL must illuminate before the end of the first engine start portion of the exhaust emission test • If MIL illuminates prior to emissions exceeding applicable OTL, no further demonstration is required. • If MIL does not illuminate either the OTL or the OBD II system is not acceptable. • If MIL first illuminates after emissions | (h)(6) | <u>Evaluation Protocol:</u> <ul style="list-style-type: none"> • MIL shall illuminate upon detection of the tested component when measured over the NEDC test cycle. • Such defective components shall not cause emissions to exceed the OTL by more than 20%. | [23] 3.3.2 & App.1 |

| CARB OBD-II (Ref.[21]) | Ref | Euro OBD (Ref.[1] & [23]) | Ref |
|--|----------------|---|-------------|
| exceed the OTL, the test vehicle shall be retested with the component adjusted so that the MIL will illuminate before emissions exceed the OTL. | | | |
| <u>Confirmatory Testing:</u> <ul style="list-style-type: none"> CARB may within 6 months of approving the data submitted by the manufacturer, request to perform confirmatory testing to verify the emission test data submitted by the manufacturer Vehicles may be recalled for corrective action if a representative sample fails the Confirmatory Testing | (h)(7) | <u>Confirmatory Testing:</u> <p>Not required as the original demonstration test is witnessed by the certification authorities</p> | N/A |
| <u>Deficiencies:</u> <p>Factors considered:</p> <ul style="list-style-type: none"> Extent to which the OBD requirements are satisfied Demonstrated good-faith effort to meet the requirements in full Manufacturers are subject to fines of either \$50 or \$25 per deficiency per vehicle for each non-complying system starting with the third deficiency. Total fines may not exceed \$500 per vehicle. Deficiencies may not be retroactively granted after certification | (k) | <u>Deficiencies:</u> <p>Factors considered:</p> <ul style="list-style-type: none"> Extent to which compliance is not feasible or is unreasonable Deficiency not acceptable where there is a complete lack of monitor No fines are imposed Retrospective deficiencies are allowed | [23] 4.5 |
| <u>In Use Performance Monitoring</u> <ul style="list-style-type: none"> IUMPR ≥ 0.336 for PM Filter and NO_x After-Treatment related monitors At least 500 miles of vehicle operation needed to increment IUPR counter for PM Filter | (d) (3.2.1) | <u>In Use Performance Monitoring</u> <ul style="list-style-type: none"> IUPR ≥ 0.1 for all monitors At least 800 cumulative kilometres of vehicle operation must be experienced in order to increment the IUPR counter for PM Filter | [23](7) |

2.3 Vehicles certified under CARB PM and NO_x OBD requirements

The flow-chart below outlines the process used to collect the data provided under this section of the report.

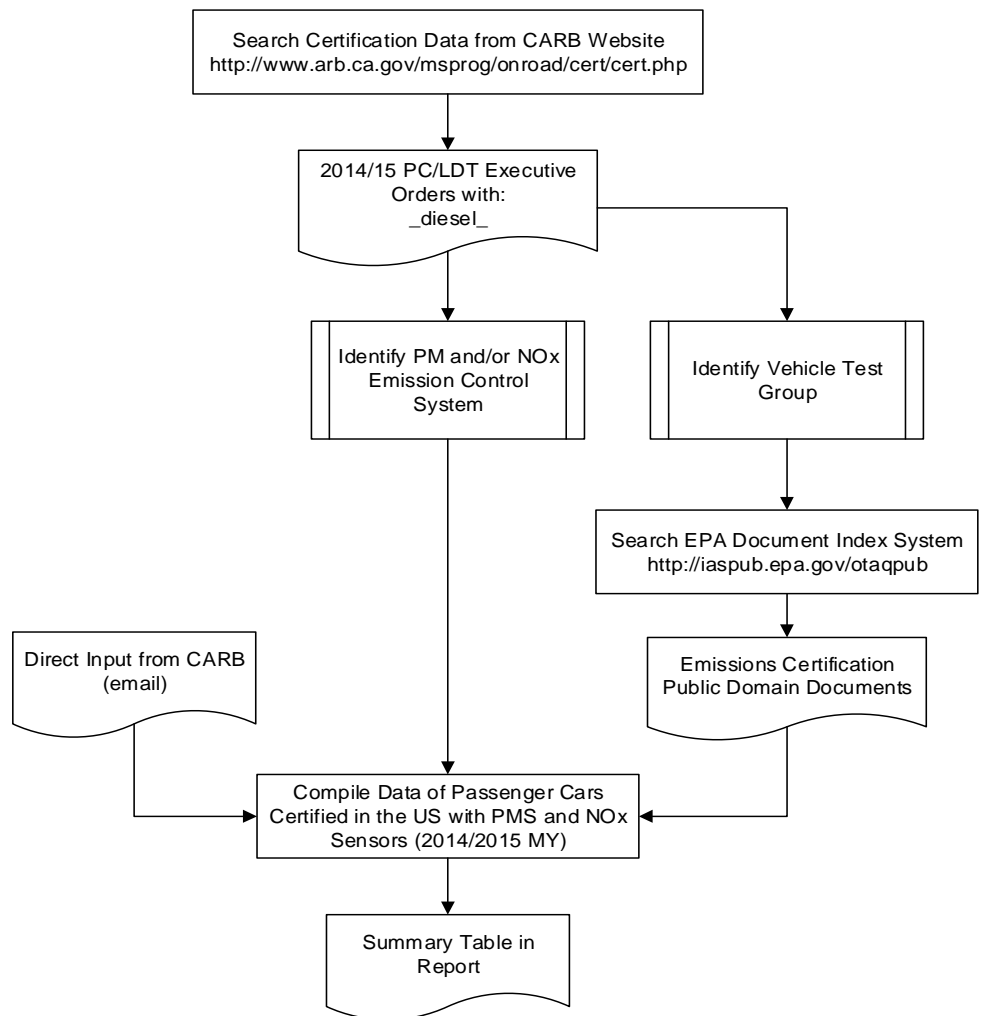


Figure 2.2: Flowchart illustrating the process used to collect the data concerning the vehicles certified under CARB PM and NOx OBD requirements

2.3.1 Vehicles certified under latest stringent PM, NOx OBD requirements

In Table 2.2 and Table 2.3 the 2014 MY and 2015 MY Passenger Cars & LDT's with PM Sensor and NOx Sensor are summarized.

Table 2.2: 2014MY Passenger Cars & LDT's with PM Sensor and NOx Sensor

| Vehicle Make | Model | Engine Size (Litres) | Vehicle Type | Emission Standard | OBD-II | PM Emissions [g/mile] | NOx Emissions [g/mile] | NOXS | PMS |
|----------------|-----------------------|----------------------|--------------|-------------------|---------|---|---|------|-----|
| | | | | | | STD: 0.01 g/mile OBD OTL: 0.018 g/mile | STD: 0.07 g/mile OBD OTL: 0.123 g/mile | | |
| Mercedes | E250 BluTec 4Matic | 2.1 | PC | Bin 5 ULEV 2 | Partial | 0.002 | 0.050 | • | • |
| Mercedes | ML250 BluTec 4Matic | 2.1 | PC | Bin 5 ULEV 2 | Partial | 0.002 | 0.050 | • | • |
| Mercedes | GLK250 BluTec 4Matic | 2.1 | LDT2 | Bin 5 ULEV 2 | Partial | 0.002 | 0.050 | • | • |
| Porsche | Cayenne | 3 | LDT3 | ULEV 2 | Partial | 0.002 | 0.040 | • | • |
| VW | Touareg | 3 | LDT3 | ULEV 2 | Partial | 0.002 | 0.040 | • | • |
| AUDI | Q7 | 3 | LDT4 | ULEV 2 | Partial | 0.001 | 0.040 | • | • |
| AUDI | A6, A7, A8, A8L, Q5 | 3 | PC, LDT2 | ULEV 2 | Partial | 0.003 | 0.040 | • | • |
| BMW | 328d | 2 | PC | Bin 5 ULEV 2 | Partial | 0.001 | 0.010 | | • |
| BMW | 535d | 3 | PC | Bin 5 ULEV 2 | Partial | 0.001 | 0.030 | • | • |
| BMW | X5 xDrive35d | 3 | LDT4 | Bin 5 ULEV 2 | Partial | 0.000 | 0.030 | • | • |
| Mercedes | ML350 BluTec 4Matic | 3 | LDT4 | Bin 5 ULEV 2 | Partial | 0.003 | 0.030 | • | • |
| Mercedes | GL350 BluTec 4Matic | 3 | LDT4 | Bin 5 ULEV 2 | Partial | 0.003 | 0.030 | • | • |
| GM (Chevrolet) | LUZ Cruze Diesel D1SC | 2 | PC | LEV160 LEV 3 | Partial | 0.001 | CERT: 0.050 g/mile (NOx+NMHC) STD: 0.160 g/mile (NOx+NMHC) | • | • |
| Chrysler | JEEP Grand Cherokee | 3 | LDT4 | Bin 5 ULEV 2 | Partial | 0.002 | 0.05 | • | • |

Table 2.3: 2015MY Passenger Cars & LDT's with PM Sensor and NOx Sensor

| Vehicle Make | Model | Engine Size (Litres) | Vehicle Type | Emission Standard | OBD-II | PM Emissions [g/mile] | NOx Emissions [g/mile] | NOXS | PMS |
|--------------|---------------------|----------------------|--------------|-------------------|---------|---|---|------|-----|
| | | | | | | STD: 0.01 g/mile OBD OTL: 0.018 g/mile | STD: 0.07 g/mile OBD OTL: 0.123 g/mile | | |
| Volkswagen | Touareg | 3 | LDT3 | Bin 5 ULEV 2 | Partial | 0.002 | 0.04 | 2 | • |
| AUDI | Q7 | 3 | LDT4 | Bin 5 ULEV 2 | Partial | 0.001 | 0.04 | 2 | • |
| AUDI | A6, A7, A8, A8L, Q5 | 3 | PC, LDT2 | Bin 5 ULEV 2 | Partial | 0.003 | 0.04 | 2 | • |
| BMW | 328d | 2 | PC | Bin 5 ULEV 2 | Partial | 0.001 | 0.01 | 2 | • |
| BMW | 535d | 3 | PC | Bin 5 ULEV 2 | Partial | 0.001 | 0.03 | 2 | • |
| BMW | X3 xDrive28d | 2 | LDT2 | Bin 5 ULEV 2 | Partial | 0.000 | 0.01 | 2 | • |
| BMW | 535d xDrive | 3 | PC | Bin 5 ULEV 2 | Partial | 0.001 | 0.03 | 2 | • |
| BMW | 740Ld xDrive | 3 | PC | Bin 5 ULEV 2 | Partial | 0.001 | 0.03 | 2 | • |

2.3.2 Deficiencies used by vehicle manufacturers

The OBD-II status for all vehicles listed in Table 2.2 and Table 2.3 is described as “Partial”. This means the certification was granted with one or two deficiencies. These deficiencies may apply to any part of the OBD System. However where deficiencies applied to PM sensor monitoring, the reason has been given by CARB as “Deficiency for PM Sensor not detecting a fault in a single FTP cycle”.

2.4 Correlating PM Emission Results from US to EU

2.4.1 Typical Emissions Levels and Influences

As Table 2.2 shows, recent US certification values for PM emissions of diesel vehicles are substantially below the approval standard of 0.010g/mile – or 10mg/mile. In European terms, this limit value equates to ~6.25mg/km. Analysis of the quoted certification values indicates emissions levels well below the certification threshold, of between 0 and 3 mg/mile (0 – 1.9mg/km): due to the application of efficient wall-flow DPFs.

Ricardo experience of testing Euro 4 and 5 DPF-equipped diesel vehicles is consistent with this observation (Figure 2.3) and with the emissions levels, despite the differences between European and US methodologies for determining gravimetric PM (see below). With the possible exception of maximal DPF regeneration (those that fully complete during a single emissions cycle), where PM from one-off tests can exceed 10mg/km, post-DPF particulate emissions are typically <1mg/km, and 2mg/km would be an ‘unusually high’ result. Off the 300 test results shown in Figure 2.3, only 16 were above 1.5mg/km and the majority were below 0.5mg/km.

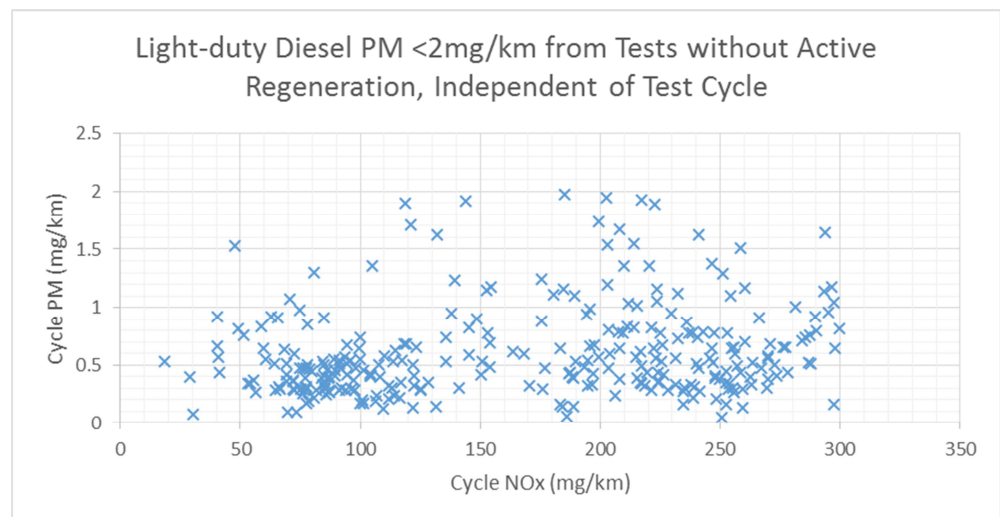


Figure 2.3: Light-duty Diesel PM at Ricardo, < 2mg/km

The main reason for these consistently low PM results, is that European OEMs tend to certify their vehicles with a stable DPF soot-fill that ensures very high filtration efficiency in order to safely meet particle number requirements. This will usually be in excess of 99%, and more likely >99.8%.

This stable soot fill has two effects:

- It ensures that the soot on the DPF acts as the main capture medium and it efficiently removes nearly all the constituents of PM, including carbon,

metallic ash, hydrocarbons of various volatilities and other volatile components such as sulphates and nitrates. In fact, despite the low PM masses observed, the solid particles penetrating the DPF may comprise as little as 0.5%, but typically 5%, of the collected material – the rest being the ‘volatile artefact’.

- This artefact is the volatile and semi-volatile materials collected by the filter medium, that may be gas-phase HCs already quantified by FID, or residual materials contributed by the dilution tunnel.
- The presence of the dense soot layer (soot cake) means that, irrespective of drive cycle, the solid PM material that penetrates the DPF is extremely low, and with the exception of cycles with very high levels of passive regeneration – whose emissions may approach 2 mg/km, the PM mass emissions are dominated by the volatile artefact.
 - This tends to normalise the emissions from different cycles and they can't be distinguished.

2.4.2 *Correlation between PM emissions from US and European Cycles*

When attempting to correlate US-FTP PM emissions with those of the NEDC, we would expect similar levels to be recorded on a g/mile (g/km) basis from the two cycles.

There is an important difference between US and EU measurements though: the US approach uses a filter medium that has a much lower affinity for volatiles, so this would tend towards a slightly lower emission from the FTP than NEDC, as the volatile artefact is reduced.

However, the repeatability of the PM methods, at <1mg/km, may approach 50% in mainstream (not ultra clean) labs, where conventional and development vehicles are tested alongside DPF diesels. In these cases, PM backgrounds of >1mg/km may be found and these will mask cycle-to-cycle differences.

Should a test cycle contain high levels of passive regeneration (for example, US06) this may cause the DPF's filtration efficiency to fall slightly for soot, resulting in higher emissions of solid particles. However, it is likely that any increases in mass emissions would be undetectable when averaged across the cycle. Increases in particle number would be observed though.

Considering the actual certification values in Table 2.2 of 1-3 mg/mile, it is highly likely that similar values would also be observed on the NEDC.

One possible issue for correlation could arise if a very long drive cycle (e.g. 100km) was compared with a very short one (10km). The storage capacity of a sample filter for volatile materials (in the absence of collected soot) is finite. If this storage threshold is exceeded during both cycles, the finite mass collected is divided by 10km in one case and by 100km in the other. This could result in reported mass emissions that differ by an order of magnitude.

2.5 **Technologies to meet NO_x OBD requirements**

Title 13 of the California Code of Regulations (CCR) §1961.2 contains the LEV III exhaust emission standards for MY 2015+ passenger cars

The table below gives most recent amendment of CCR §1961.2 as given in the Final Regulation Order as amended on December 6, 2012.

Table 2.4: The most recent amendment of CCR §1961.2 as given in the Final Regulation Order as amended on December 6, 2012

| Vehicle Emission Category | NMOG + NOx (g/mile) | Carbon Monoxide (g/mile) | Formaldehyde (mg/mile) | PM (g/mile) |
|---------------------------|---------------------|--------------------------|------------------------|-------------|
| LEV160 | 0.160 | 4.2 | 4 | 0.01 |
| ULEV125 | 0.125 | 2.1 | 4 | 0.01 |
| ULEV70 | 0.070 | 1.7 | 4 | 0.01 |
| ULEV50 | 0.050 | 1.7 | 4 | 0.01 |
| SULEV30 | 0.030 | 1.0 | 4 | 0.01 |
| SULEV20 | 0.020 | 1.0 | 4 | 0.01 |

There is a clear trend in the above table for persistent reduction in NOx emission levels. This will mean a requirement to operate the SCR at high NOx conversion efficiency levels.

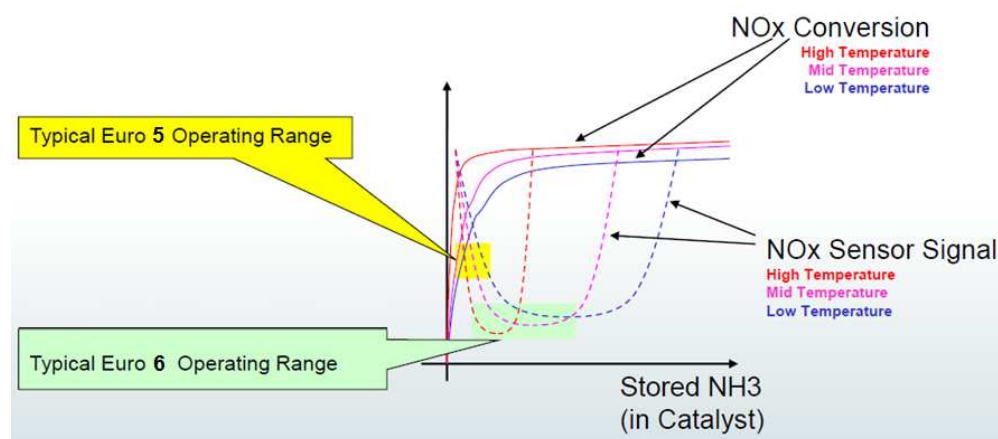


Figure 2.4: Typical SCR operating ranges for achieving different emission levels

The typical SCR operating range to achieve Euro 6 emissions is in the 150-190ppm NOx range. Comparing this to typical NOx Sensor accuracy:

| Description | Details | Generation 2.0 | Generation 2.5 |
|-------------|-------------|----------------|----------------|
| Tolerance | 0 – 100 ppm | ±15ppm | ±10ppm |
| | > 100 ppm | ±15 % | ±10 % |

For an average NOx level of 180ppm for a good performing system (SCR efficiency at 90 percent) a sensor with 10% tolerance below nominal will present conversion efficiency of 80% when targeting 90%.

OBD threshold of 2 x Emission Standard will be reached when the conversion efficiency decreases to ~84 percent.

There would be significant difficulty to monitor SCR NOx conversion efficiency in a situation where a high efficiency is required to meet the increasingly stringent

emission standards. This is because very small conversion efficiency drop needs to be monitored & detected as failure.

If the generation 2.5 sensor is used to meet the more stringent parts of LEV III exhaust emission standards for MY 2015+ passenger cars, there will be too little separation between a failure and passing conditions to assure a robust monitoring strategy

The figure below shows a schematic of NO_x conversion efficiency as a function of the NH₃ storage capacity of the SCR

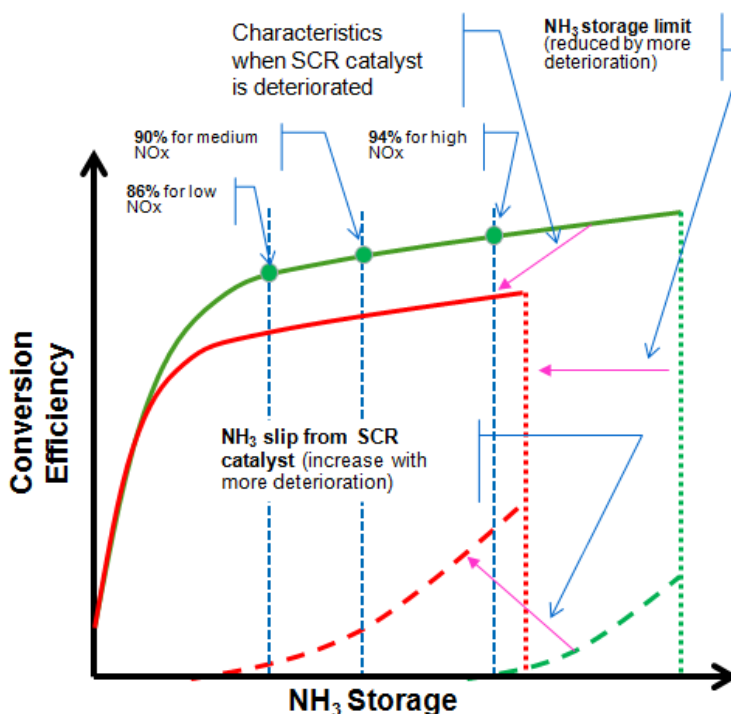


Figure 2.5: Schematic depiction of NO_x conversion efficiency as a function of the NH₃ storage capacity of the SCR

As the SCR catalyst is deteriorated the NH₃ storage capacity is seen to exhibit significant reduction.

Based on this relationship as well as Ricardo in house emission data, a more effective and robust SCR NO_x conversion efficiency monitor can be realised by making use of NH₃ storage estimate in combination with NO_x Sensor signal only. It is expected that use of NH₃ may also play an instrumental role in adding further fidelity to the NH₃ estimation strategies.

In order to prepare towards stringent NO_x detection requirements for NO_x aftertreatment management and reagent dosage control as well as for OBD purposes, NO_x sensor development is pointing towards further improvement of accuracy. Manufacturer information indicate accuracy for generation 3.0 similar to generation 2.5 (± 10 ppm for aged sensors but improved sensor dynamic performance compared to gen. 2.5) but it is anticipated to go down to ± 5 ppm at concentrations < 50 ppm in generation 4.0 (i.e. 2018).

According to NO_x sensor manufacturer information, there are numerical methods and modelling for both sensor and engine and SCR system performance that can be applied to overcome sensor accuracy degradation and achieve OBD detection

targets. Such techniques include NO_x and NO₂ emission modelling, indirect assessment of SCR performance etc. Therefore, it is not safe to draw direct conclusions on NO_x OBD requirements feasibility based on sensing hardware accuracy only.

As regards market availability, Table 2.2 and Table 2.3 include vehicles of MY 2014 and 2015 respectively that were certified in the US as being equipped with NO_x sensors. All certified vehicles were able to pass the NO_x OBD certification test against a NO_x OBD threshold of 0.123 g/mile. Therefore, the comparison of the differences between the US and EU NO_x OBD requirements may support the transferability of the existing OBD monitoring technology package to support the EU PM OBD requirements, at least using similar NO_x sensing technologies.

2.6 Technologies to meet PM OBD requirements

PM emission standards already with the implementation of Euro 5 and consequently Euro 6, dictated the need of a highly efficient PM aftertreatment technology, the Diesel Particulate Filter (DPF). The efficiency of a DPF exceeding under specific conditions 99.5% of filtration efficiency essentially filters all particulate emissions of the engine and is periodically regenerated (temperature increase) in order to burn off the accumulated particulates and clean-off the filter. The combination of the stringent PM emission and OBD limits with the high filtration efficiency of the DPF means that any minor malfunction (e.g. ring-off crack) that will result in exhaust leakage through the DPF may lead to considerable increase of DPF-out emissions beyond the limits of the legislation (Figure 2.6).

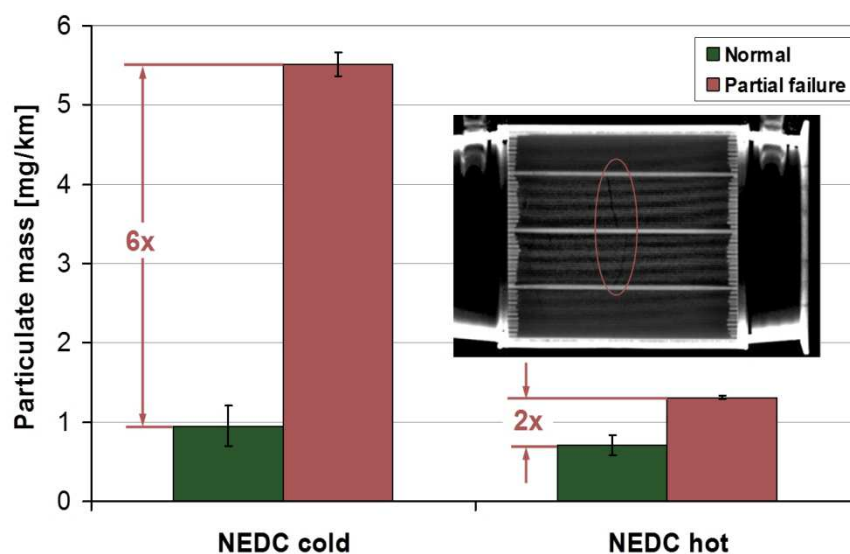


Figure 2.6: Effect of a partial failure on vehicle emissions (clean DPF before both tests)

The need of detection of such gradual but marginal emission increases triggered the development of several technologies to meet the needs of PM OBD requirements. Such technologies have already been presented in Ref.[3] and consist essentially of sensors being able to assess soot concentration either as an integrated value over a period of vehicle operation (accumulative sensors) or in real time. The main technologies along with some major developer examples are as follows (illustration in Figure 2.7):

| | |
|------------------------|---|
| Accumulative: | Bosch, Continental, Delphi, Electricfil, Stoneridge |
| Real time: | NGK-NTK, Pegasor, Emisense |
| Secondary soot filter: | Innexsys |
| Radio frequency: | General Electric Accusolve |



Figure 2.7: Examples of PM OBD technologies

In addition to the soot sensing part, an OBD algorithm is required that will correlate the output of the sensor and the operating profile of the vehicle during the period of diagnosis to vehicle emissions over the type-approval cycle. The challenge of this requirement is defined by the sensitivity and stability of the sensor as well as the driving profiles and the legislation requirement.

At the date of the completion of this report, the above sensors including the accumulative sensors were found to be at different stages of development with varying probability of finally being passed to mass production in due time. The dominating technology which was adopted and was in the process of OBD implementation by most diesel vehicle manufacturers was the accumulative sensor.

The accumulative sensors are based on the principle of measuring the resistance reduction of an array of electrodes exposed to exhaust gas which is caused by electrical bridges created by the soot that is accumulating between the electrodes. These sensors gradually accumulate soot until a certain saturation point. At that point the sensor element is being heated to clean-off the accumulated soot. Therefore, the time needed for the sensor to reach from completely clean state to soot saturation is proportional to the average soot concentration in the exhaust gas that has passed over the sensor element.

The signal of accumulative sensors is sensitive to parameters such as exhaust gas humidity (temperature must be above due point), velocity, NO₂ content etc. Therefore advanced models need to be employed in order to compensate for the effect of these various exhaust characteristics. This poses additional challenges on the implementation of these sensors on specific vehicle and aftertreatment setups.

As regards market availability, Table 2.2 and Table 2.3 include vehicles of MY 2014 and 2015 respectively that were certified in the US as being equipped with PM OBD technologies. All these vehicles together with some vehicles of MY 2013 were found to be equipped with an accumulative soot sensor. All certified vehicles were able to pass the PM OBD certification test with the exception of two vehicles declaring deficiencies as "PM Sensor not detecting a fault in a single FTP cycle".

Based on the above, the accumulative soot sensor can be considered as a proven concept since it has already been installed on US market vehicles and in-field operation. In addition to the sensor successful application, the feasibility of a robust OBD algorithm is also verified by the fact that there are existing working applications.

The task of this assessment as already set is to compare the differences between the US and EU PM OBD requirements and decide whether the successful implementation of a PM OBD detection system is US vehicle models can support the feasibility of the EU PM OBD requirements at least using similar PM sensing technologies.

3 Relation between EU and worldwide OBD requirements

As already presented in previous sections of this report, vehicle manufacturers have already successfully implemented OBD monitoring systems able to cope with stringent PM and NOx requirements as set by the US CARB regulations. These systems may be able to cope with the Euro 6 OBD requirement as well. A direct comparison based on limit values though is not possible due to the differences between EU and US type-approval procedures as outlined in section 2.2 of this report.


The main difference between the EU and CARB type-approval procedures is the driving cycle(s) used for type-approval and consequently the vehicle operation introduced by these driving cycles under which emissions to be compared with limits are being estimated. In order to have a cost efficient assessment, a desktop study was decided to be performed in order to investigate these differences. The modelling and simulation work in combination with some testing that was deemed necessary to get more accurate results are being presented in this chapter.

3.1 Vehicle and sensor modelling to correlate US and EU requirements

Simulation of vehicle and OBD performance was decided to be performed using the AVL Cruise[®] vehicle and powertrain simulation tool for modelling soot and PM emissions and Exothermia Axisuite[®] for modelling of the exhaust aftertreatment devices in the case of NOx aftertreatment. The simulations were run over the NEDC used in EU, as well as the FTP-75 used in USA. Modelling was performed by coupling to the basic models well operating as well as failed DPF and NOx aftertreatment systems for assessing PM and NOx OBD systems respectively.

As regards the characteristics of the vehicle to be modelled, a passenger car with a 2.2 diesel Euro 4 engine was selected and simulated to operate with a DPF and an SCR system with urea injection in order to comply with both Euro 6 and Bin 5 ULEV 2 emission standards. The specifications of the actual test vehicle and exhaust aftertreatment are summarized in Table 3.1.

Table 3.1: Characteristics of the vehicle model used for simulations and measurements

| | | |
|----------------|---|---|
| Model, model | Honda Accord, 2.2 i-CTDi |  |
| Engine | 4 cyl., diesel, Common rail, Turbo, Direct Injection, 2200 cc, 100 kW | |
| Gearbox | Manual | |
| Aftertreatment | Euro 4 (original) | |
| | Euro 6, Bin 5, ULEV 2 (simulated) | |
| | | EGR, 2-stage DOC with DeNOx characteristics DPF, SCR |

This vehicle was within the common pool of engine capacities met in European and USA fleets at the low engine capacity end of the US diesel fleet. In addition, measurement and simulation data were available for this vehicle at LAT as well as an actual vehicle for chassis dynamometer tests and an actual engine for engine dynamometer tests in case this was deemed necessary. As it will be discussed later in this text, model calibration was performed and validated using already available

tests and in addition some tests for the assessment of engine-out NO_x emissions were performed on the actual vehicle.

3.2 Particle Matter (PM) emission modelling and results

3.2.1 Description of modelling

As previously discussed, the main monitoring technology that was identified in market vehicles in USA is the accumulative soot sensor. The accumulative soot sensor is an instrument able to produce a signal that is correlated to the average soot concentration over a certain period of operation. Therefore, in order to simulate the performance of the sensor on a vehicle, a model is needed capable of accurately estimating cumulative soot emissions over the cycle of operation of a soot sensor (i.e. in the order of 100 s, 0.01 Hz). This means that in order to validate the model before the final application, any operating cycle regardless of its transient characteristics would be sufficient. Therefore validation was performed over the NEDC for which measurement data were available to compare against simulation results and not the FTP-75 cycle for which no real time measurement data for soot were available.

The framework model that was chosen for the simulations was IAV VeLoDyn[®]. VeLoDyn[®] (acronym for VEHICLE LONGitudinal DYNamics) is a simulation tool for managing and simulating motor-vehicle powertrains and it works as a part of the Matlab Library just like Simulink. The higher-order Model Manager of VeLoDyn[®] makes very easy work of archiving and standardizing Simulink models. VeLoDyn[®] works on the basis of so-called carrier blocks allowing the addition of any custom-made blocks for modelling various vehicle subsystems in a customized way. These blocks incorporate the signals from any Simulink block into a bus structure and provide a database holding all the information necessary for a model.

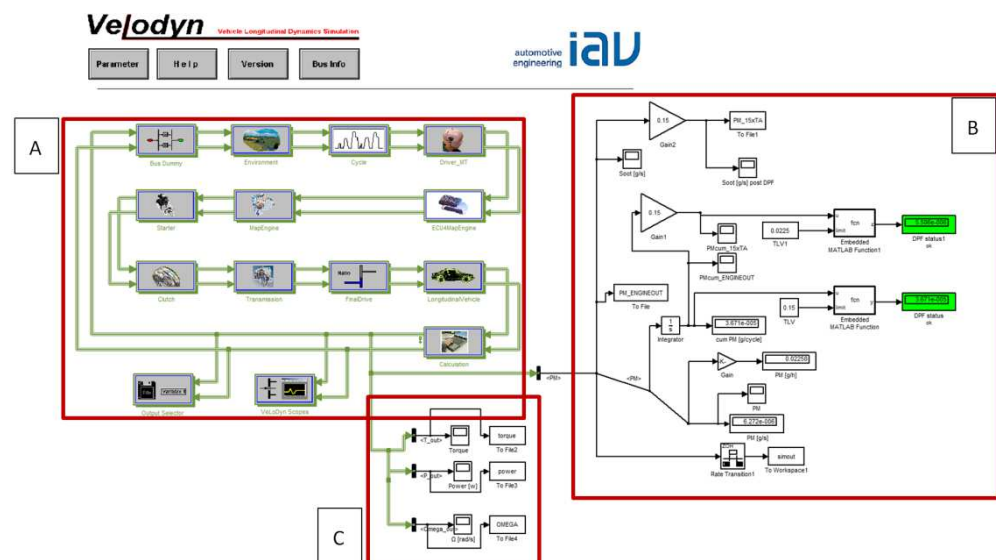


Figure 3.1: The VeLoDyn model as configured for PM model validation and simulations over the NEDC and FTP-75

It must be clarified that VeLoDyn[®] does not distinguish Particulate Matter (PM) and soot but refers only to PM. Since though calculations are based on user-defined emission models, these models were created on the basis of soot. The soot model was calibrated using soot concentration data collected on the chassis dynamometer

over the NEDC and real world driving cycles such as the Artemis Urban cycle as well as engine maps derived over engine dynamometer testing. An example of the static engine maps produced during the calibration of the model is shown in Figure 3.2.

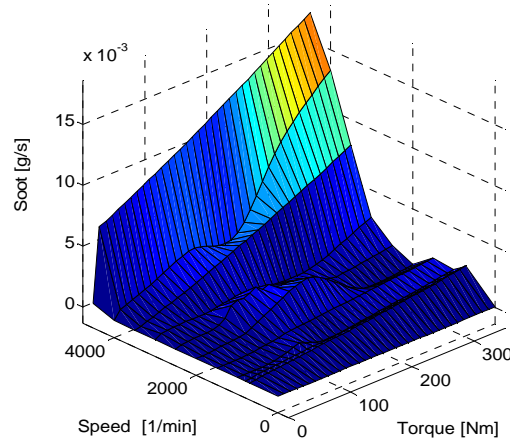


Figure 3.2: Engine-out soot map

Coupling the soot model to VeLoDyn[®] vehicle dynamics output, real time engine-out soot emissions were estimated. At this point a DPF model was coupled in order to simulate the filtration efficiency at different levels of performance ranging from an intact DPF up to a DPF failed at the OBD threshold limit of either the EU or the CARB legislation.

An optimization round was then performed in order to optimize the performance of the model. The validation at each step was performed against data collected over the type-approval NEDC as well as real world driving cycles such as the Artemis Urban. An example of the performance of the model over NEDC is shown in Figure 3.3.

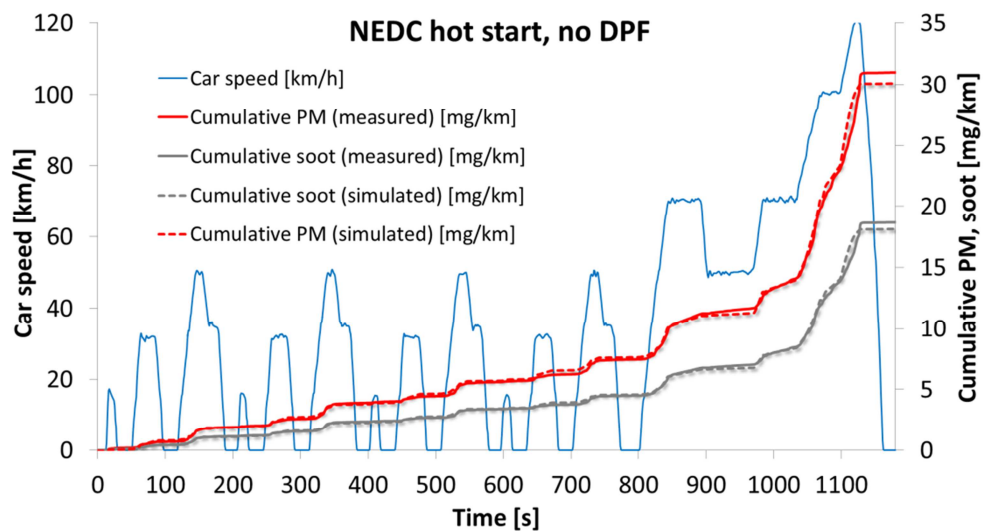


Figure 3.3: Soot, PM model validated over NEDC with hot start (simulated vs. measured cumulative mass)

As shown in Figure 3.3, the simulated engine-out cumulative emissions are in good agreement with the measured cumulative emissions over the whole duration of the NEDC cycle. A small deviation of the model is observed only after the last acceleration of the NEDC where temperature increases, speed reaches 120 km/h

and engine load is high. Compensating for this error was leading to accuracy deterioration to the simulation of the rest of the cycle. Since this high speed level is not included in FTP-75 and is observed for a limited time in NEDC it was decided to keep the presented optimal solution which was the most accurate for more than 98% of the NEDC driving cycle and definitely the most accurate for all other cycles with slightly lower top speed like the FTP-75.

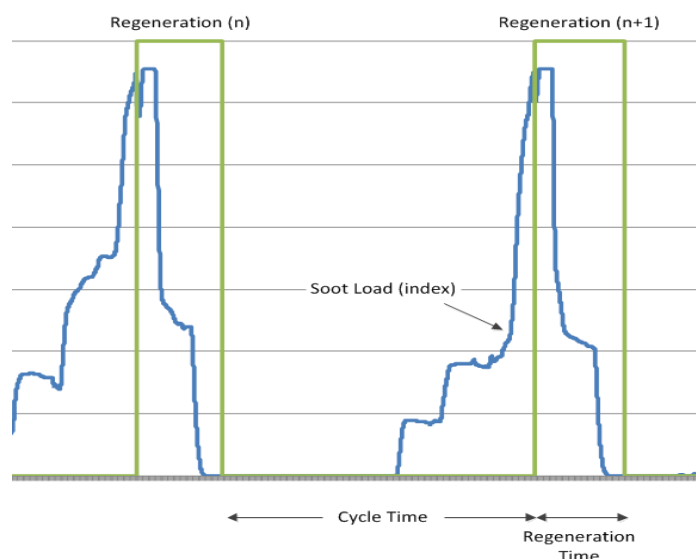


Figure 3.4: Periodic operation of a soot sensor

Next step to the simulation was the addition of a DPF model. The DPF filtration efficiency was modelled in order to simulate malfunctions with soot leakage that result in exceedance of EU and US OBD threshold limits. The OBD threshold limits are defined against emissions measured over cold start engine conditions. On the other hand OBD type-approval is performed over hot start cycles. Therefore, in order to calculate the DPF failure level, first the cold start OTL emissions were converted (reduced) to equivalent hot start emissions. In house data at LAT indicated that for NEDC cold start PM emissions are expected to be 1.25 times higher than NEDC hot start PM emissions. On the other hand FTP-75 emissions do not differ significantly between hot start and cold start emissions. This is due to the higher length of the FTP-75 cycle that reduces the cold start effect time contribution. In addition, the 1st part of FTP-75 which is the one affected by cold start is underweighted in the PM calculation by a factor of $0.43/(0.43+1+0.57)$. The ratio PM/soot was also taken into account for the respective conversions. For more details see also discussion in section 2.4.2. The parameters affecting the above calculation are summarized in Table 3.2. The emissions of hot start NEDC and FTP-75 that result in exceedance of the EU and US OBD OTLs are 9.6 mg/km and 10.9 mg/km respectively.

Table 3.2: Calculation of equivalent emissions for hot start cycles for OBD type-approval

| | OTL (cold start) | | Ratio: | OTL (hot start) | Ratio: |
|---------------|------------------|-------|------------------|-----------------|---------|
| | mg/mile | mg/km | Cold / Hot start | mg/km | Soot/PM |
| FTP-75 | 17.5 | 10.9 | 1 | 10.9 | 0.52 |
| NEDC | - | 12.0 | 1.25 | 9.6 | 0.58 |

In the last step of model the simulation of a cumulative soot sensor was added. As shown in Figure 3.4, a cumulative soot sensor operates in a periodic manner. The

signal of a clean soot sensor is increasing if expressed in excitation current units (or decreasing if expressed in electrical resistance units) as soot accumulates on the sensor element and resistance of the electrode gaps is decreasing. As soon as the sensor saturates with soot (or, in other words, the element resistances reaches its minimum value), the sensor measurement stops, the element is heated up to be regenerated and deposited soot is burnt. When regeneration ends, the sensor enters measurement mode again and soot starts accumulating on the sensor. When a critical amount of soot accumulates on the sensor, the signal exits a dead zone and begins increasing again. The time from the end of sensor regeneration until the beginning of the next sensor regeneration is the cycle time and is in fact the quantity that can be correlated to the average soot concentration during this time.

The critical parameter to judge whether a sensor is capable of performing a diagnosis over a certain operation cycle, given sensors' good repeatability, is the ability of the sensor to complete at least one sensor loading cycle. In order to model sensor performance over NEDC and FTP-75, a dummy sensor behaviour model was created. This very basic model consisted of a gain associating sensor signal increase to real time soot emission rate (e.g. expressed in g/s). The critical parameter to be assessed was the sensor soot accumulation rate and sensor soot saturation point.

Data in Figure 3.5 were collected from charts in public presentations of soot sensor developers as well as direct communication. Depending on vehicle exhaust characteristics (temperature, velocity, composition etc.) cumulative sensors seem to have a relatively common saturation level. An average value was derived from all sensor data and used to compile an average accumulative sensor model. This simplified sensor model uses soot emissions as input and produces a signal similar to the one shown in Figure 3.4. In addition, a period of 100 s was assumed to be needed by the sensors for regeneration both in the beginning of a test cycle (i.e. after engine start) and whenever the sensor was saturated with soot.

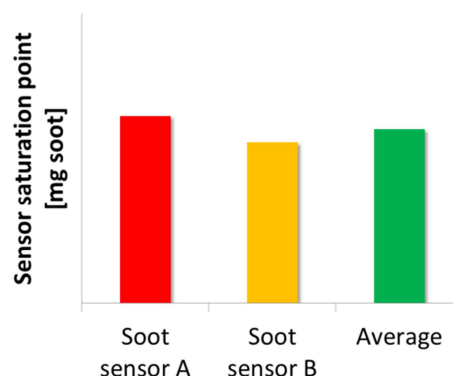


Figure 3.5: Soot sensor saturation mass

An overview of the complete model and evaluation is shown in Figure 3.6. Summarizing what was presented in this section, modelling is performed for the EU type-approval and the US certification failure level separately. Driving cycle data are inputted to the VeLoDyn[®] model to simulate vehicle dynamics. These data are then passed to the soot model that estimates the transient profile of engine-out soot emissions during the driving cycle. The engine-out emissions are then fed to a DPF filtration efficiency model that is calibrated to simulate a failure leading to exceedance of the OTL and is different for the EU and the CARB case. The output

of the DPF model is then fed to the Soot sensor model which, taking into account the cumulative soot emissions, reproduces the signal of a “generic” soot sensor. The emission profile and number of successful monitoring events (= complete sensor cycles) are finally compared to determine the successful completion of an OBD monitoring event.

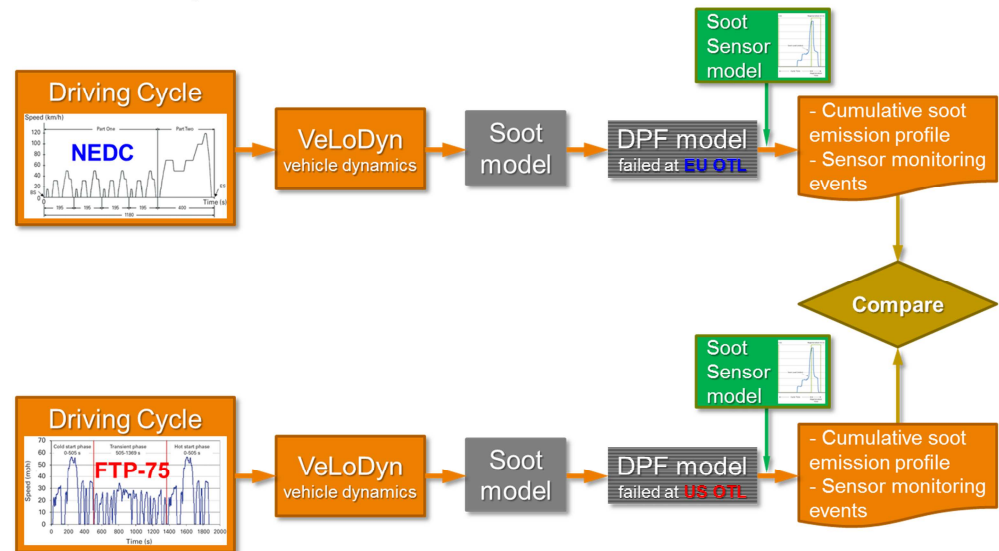


Figure 3.6: Modelling and evaluation of PM OBD system performance

3.2.2 Results of the PM simulations

As already discussed, two simulations were run for PM for two cases:

- CARB FTP-75
- EU NEDC

Figure 3.7 and Figure 3.8 show the results of the simulation for the two driving cycles. It has to be noted that:

- PM is calculated from soot using a fixed, driving-cycle dependent, soot over PM ratio.
- Cumulative PM is scaled to mg/km by dividing the real time cumulative PM emissions with total cycle driving distance.

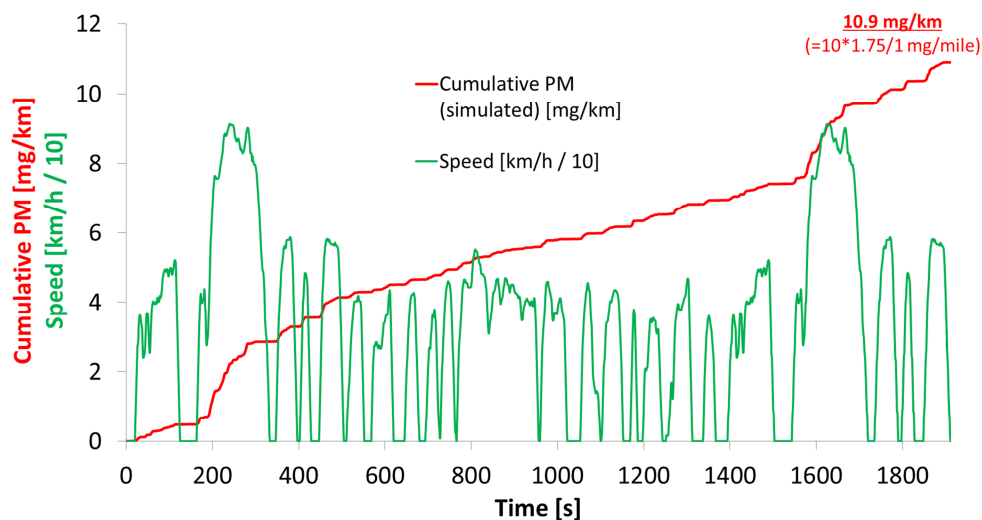


Figure 3.7: Cumulative PM emissions simulated over FTP-75 with failed DPF

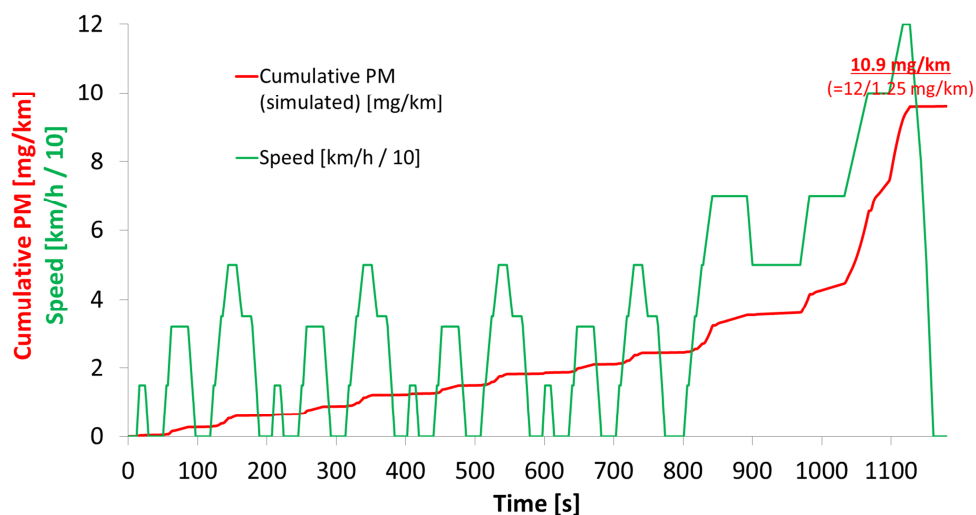


Figure 3.8: Cumulative PM emissions simulated over NEDC with failed DPF

As shown in Figure 3.7, cumulative PM in FTP-75 increases at a steady rate with the exception of two high acceleration areas where it increases more rapidly due to the high soot emissions associated to the highly transient intense accelerations. Cumulative PM similarly increase at a steady rate for NEDC in Figure 3.8 during the UDC part of the cycle (first 780 s). In the EUDC part of the cycle (last 400 s) the increase rate is higher due to the high accelerations up to high speeds. The above means that soot is going to be deposited at a relatively stable rate on the soot sensor for both US and EU cycles, posing therefore a similar measurement challenge.

The results of the sensor simulation for FTP-75 and NEDC are presented in Figure 3.9 and Figure 3.10 respectively. In these figures the blue line corresponds to the simulated sensor signal (left y-axis) while the red and the green the cumulative PM and vehicle speed (right y-axis).

The FTP-75 driving cycle consists of four parts as indicated also on Figure 3.9:

- Phase 1a: 505 s, Cold start transient phase (1st engine start)
- Phase 2: 864 s, Stabilized phase (engine stop in the end)
- Soak: 540-660 s, Hot soak (engine off, used 600 s in all tests, simulations)
- Phase 1b: 505 s, Hot start transient phase (2nd engine start)

According to US CARB OBD requirements [21] an OBD system will successfully pass the certification test if, when tested with an artificially failed DPF at the OTL level, MIL illuminates before the end of the first engine start part of the FTP-75 cycle that is within the first 1369 s of the cycle. Furthermore, according to US regulation the MIL should illuminate before emissions exceed the OBD threshold limit.

The above are directly comparable to the EU legislation. In addition though, in the EU legislation an exceedance of the OTL by up to 20% is permitted. This means that the failed DPF to be used during the type-approval test can be failed above the OTL. In the simulations presented below, the qualified deteriorated component was set for both the US and the EU case at exactly the type-approval OBD threshold limit in order to simulate and compare the most stringent case. In addition to these though, a third simulation over NEDC was added (Figure 3.11) with a DPF failed at 1.2xEU OTL. This was added as a sensitivity run to assess the limits of detection possibility.

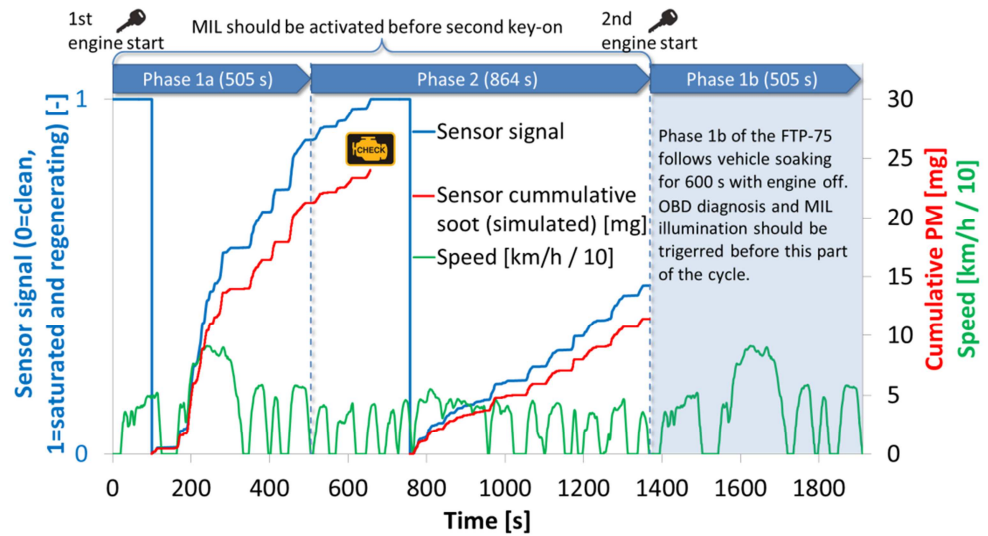


Figure 3.9: Soot sensor simulation over FTP-75 with DPF failed @ US OTL

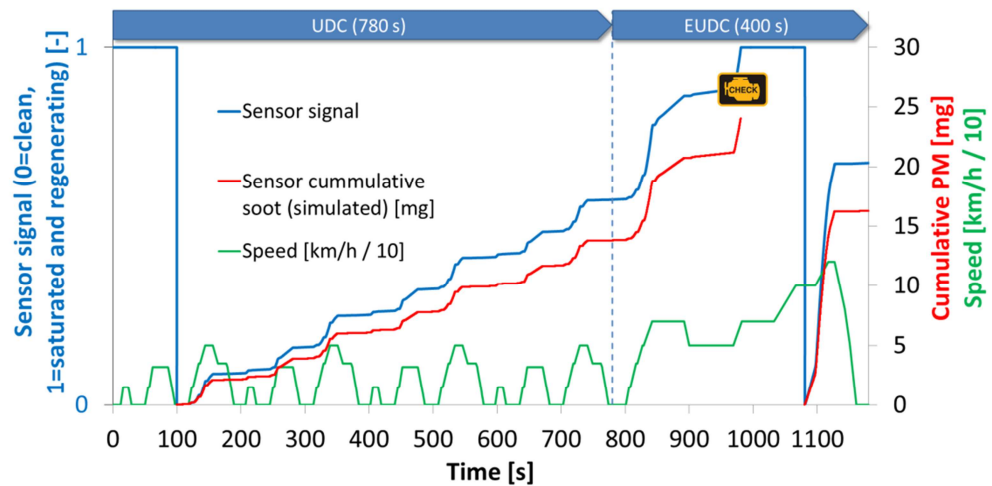


Figure 3.10: Soot sensor simulation over NEDC with DPF failed @ EU OTL

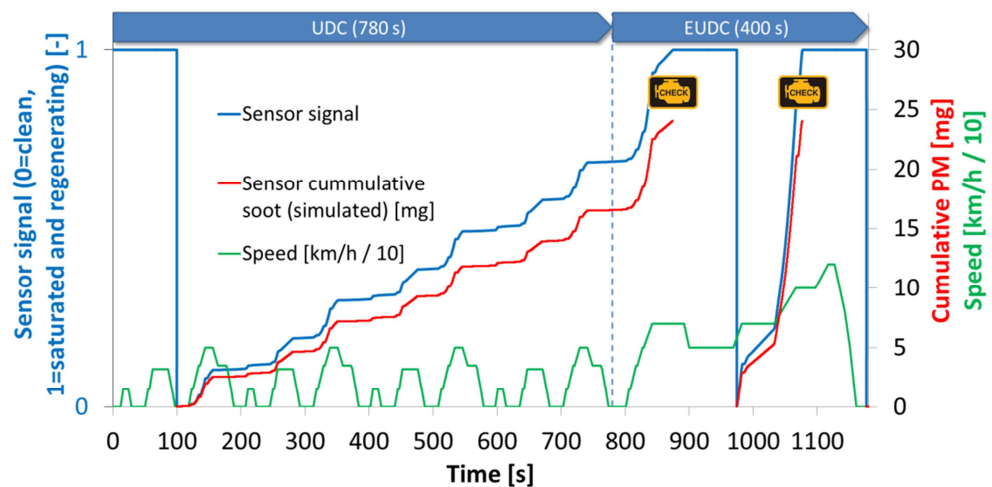


Figure 3.11: Soot sensor simulation over NEDC with DPF failed @ 1.2 x EU OTL

As seen in Figure 3.9 for the FTP-75, the soot sensor completes a full loading cycle before the middle of phase 2 (at 657.7 s). This can be considered to be a successful monitoring event (detection) and would trigger MIL illumination. It can also be seen that a second successful monitoring event is not possible before the end of phase 2 and engine stop.

Similarly in Figure 3.10 for the NEDC, the soot sensor completes a full loading cycle in the middle of EUDC (at 980.7 s). This can also be considered to be a successful monitoring event (detection) and would trigger MIL illumination.

Figure 3.11 shows the sensitivity scenario in which the EU type-approval test is run with a DPF exceeding the OTL by 20%. In this case the soot sensor is able to go through two complete loading cycles producing this way two successful monitoring events. The first monitoring event is being run with vehicle speed up to a certain level while the second monitoring event is being run during the high speed part of EUDC. This diversity in driving conditions between the two events can further enhance the detection capability by providing data to the OBD algorithm for two different areas of the vehicle and engine operating map.

Therefore, it is concluded that the latest vehicles certified by US EPA and CARB carry already OBD diagnostic technologies that can support the implementation of the Euro 6 PM OBD threshold limits.

3.3 NO_x emission modelling and results

3.3.1 *Description of modelling in combination with testing*

The main technology for NO_x OBD monitoring already applied in US certified vehicles (Figure 2.3) is the NO_x sensor which is a real time instrument. As already discussed in section 2.4.1, limited improvement of the accuracy of the NO_x sensor is expected in the coming years. Besides that though, there are ways to overcome problems associated with sensor accuracy limitations by means of ECU modelling of NO_x emissions and SCR operation and more complex OBD algorithms taking into account other engine operating parameters as well.

In order to draw the link between vehicles already successfully certified under CARB NO_x OBD requirements and the upcoming EU requirements, the most straight forward way is by assessing similarities in vehicles. The simplest approach was to assess whether a vehicle with an SCR system optimized for certification in the US can have an EU type-approval with the same NO_x aftertreatment specifications without either being evidently too high emitter or being too low emitter. The latter would mean that this vehicle in its EU version would be configured by the manufacturer with a less effective NO_x aftertreatment in order to comply with EU regulation but not being more efficient than necessary. If though a similarity is verified then what remains to be checked is the effect of the malfunction that needs to be imposed to a vehicle to be certified by CARB on the emissions over the EU type-approval procedure. If the same malfunction complies with the malfunction that needs to be imposed for the EU NO_x OBD type-approval (=achieve exceedance of the EU NO_x OTL) then the detection of this malfunction can be considered achievable given that the vehicle already was able to detect this malfunction over the CARB certification for the US market.

Following the previous discussion on NO_x detection being implemented by real time measurement and modelling, it is concluded that accurate simulation of the

transient NO_x emissions is necessary. According to the initial project planning, the assessment of NO_x OBD threshold limits would be based purely on modelling as it was done with PM. In the effort to realize this, work was divided into two parts:

- modelling of engine-out emissions over NEDC and FTP-75
- modelling of exhaust aftertreatment system, namely the Selected Catalytic Reduction (SCR) system together with the reagent dosage system.

During the first steps of model validation it was concluded that accurate engine-out NO_x modelling could not be realized in an effective way. An important piece missing for this exercise was real time NO_x data over FTP-75 to further fine tune and validate the performance of the transient NO_x emission model. Therefore it was decided to perform some specific tests at LAT on the vehicle dynamometer and measure real time NO_x and NO emissions over both NEDC and FTP-75. These measurements were performed with no NO_x aftertreatment but only DPF to simulate the expected backpressure to the engine. The test vehicle was the same as the one used for the PM modelling and has been presented in Table 3.1.

In order to simulate function, efficiency and reagent dosing of the SCR system, the SCR modelling facility of Exothermia axisuite axicat[®] was used. The input needed by this model was derived by the engine-out emission, exhaust characteristics and engine operation measurements discussed in the previous paragraph. Exothermia axisuite[®] module axicat[®] is a multi-dimensional catalyst model for the simulation of flow-through, honeycomb catalytic converters. The supported converter types include among others SCR catalysts and any custom converter by selection from a list of 70 built-in reactions or any other user-defined reactions. Reaction kinetics are expressed by Arrhenius type expressions as follows:

$$k = A \cdot e^{\frac{E}{RT}} \quad [1]$$

k rate of chemical reaction

A pre-exponential factor

E activation energy

R universal gas constant

T temperature (in Kelvin)

Two SCR systems were simulated:

- **Baseline system** was configured with optimal catalyst size and control to reduce engine-out NO_x emissions down to CARB certification limits (including optimal control of reagent injection, minimization of NH₃ slip etc.)
- **Failed system** was configured exactly as the baseline system but degradation was simulated by modifying reaction kinetics to reach emissions over FTP-75 at CARB OBD threshold limit

Both SCR scenarios were run over FTP-75 and NEDC and total cycle emissions were estimated. The values used for the simulations are summarized in Table 3.3.

Table 3.3: NO_x emission limits

| | mg/mile | mg/km |
|---|----------------|------------|
| US certification limit (Bin 5 ULEV 2, FTP-75) | 70 | 43 |
| US OBD threshold (FTP-75) | 123 (=1.75x70) | 76 |
| EU type approval limit (Euro 6, NEDC) | - | 80 |
| EU OBD threshold (Euro 6, NEDC) | - | 140 |

3.3.2 Results of the NOx simulations

The results of NOx simulations are presented in Figure 3.12 and Figure 3.13 for FTP-75 and NEDC respectively as cumulative mass emissions in g/km. In order to estimate this value for FTP-75 the three phases of the cycle were weighted according to legislation (0.43, 1.00, 0.57) and then the cumulative line in g was scaled using the weighted average emissions of the cycle to g/km.

The vehicle speed trace along with the different phases is also shown for better understanding of the driving cycle. In the end of each cumulative line the final emission value is noted along with the value it should be compared to (type-approval limit and OBD threshold). It has to be noted that engine-out emissions were divided in the chart by 2 in order to keep scale readable for the other two emission levels that were one order of magnitude lower than engine-out emissions.

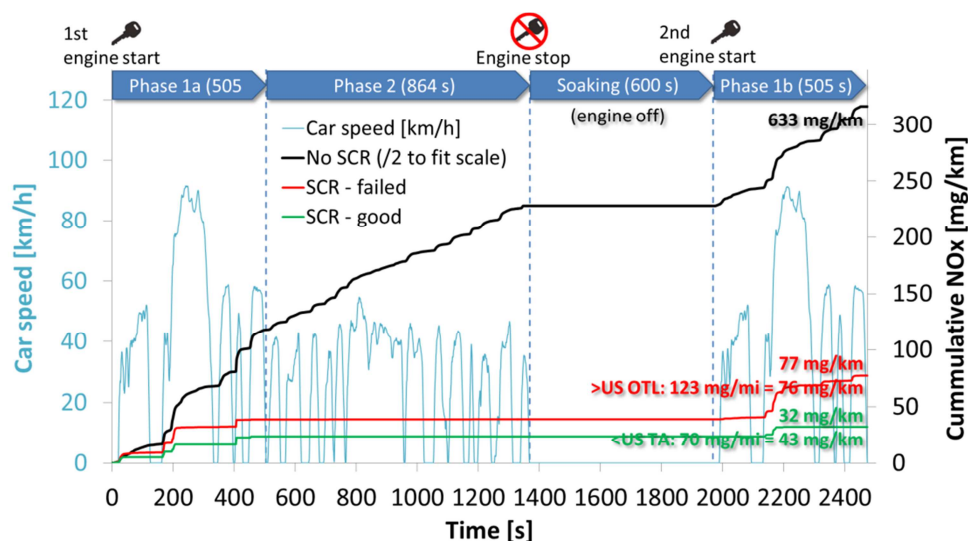


Figure 3.12: NOx emissions over FTP-75 (engine-out, good SCR, failed SCR)

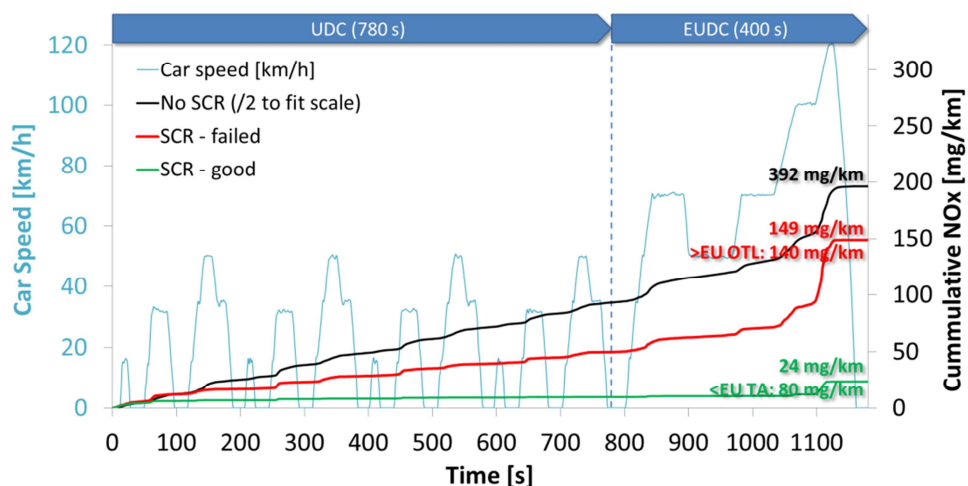


Figure 3.13: NOx emissions over NEDC (engine-out, good SCR, failed SCR)

As it can be seen in both figures, the SCR catalyst was able to reduce emissions below the type-approval limits for both FTP-75 and NEDC. The SCR was calibrated to achieve emissions on the FTP-75 cycle of 32 mg/km, moderately below the certification limit (that is 70 mg/mile = 43 mg/km). When the exact same system

was simulated over NEDC, emissions were measured at 24 mg/km which is significantly lower than the Euro 6 type-approval limit (that is 80 mg/km). In order to validate that this significant reduction is close to actual vehicle calibration, a quick assessment of vehicles that had been certified against Euro 6 during the time of completion of this report (summer 2014) was made. Data were derived from the online database of the Vehicle Certification Agency (VCA) UK. Figure 3.14 shows the cumulative distribution of NO_x emissions of Euro 6 vehicles in the database of VCA in summer 2014. It can be seen that indeed even in this early Euro 6 vehicle sample, 7.2% of the type-approved vehicles were measured to emit 24 mg/km or less of NO_x over NEDC. This means that the NO_x aftertreatment of the simulated vehicle that was optimized for US certification can also be considered a normal and not an over-performing NO_x aftertreatment system for EU type-approval.

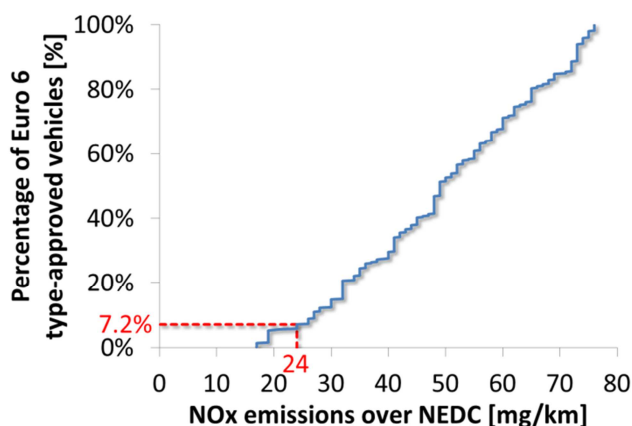


Figure 3.14: Cumulative distribution of NO_x emissions of Euro 6 vehicles (source: VCA, UK)

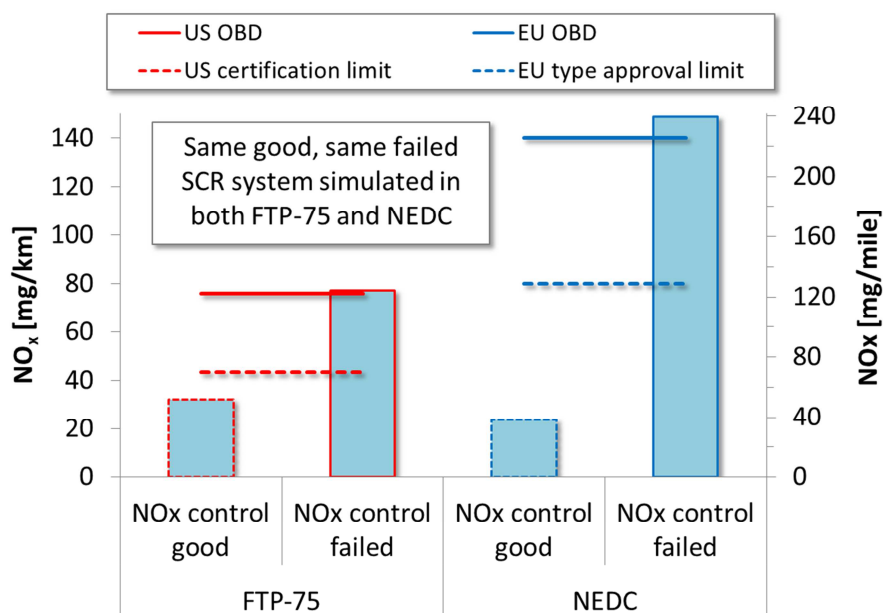


Figure 3.15: Overview of NO_x simulation results

The results of the NO_x simulations are summarized in Figure 3.15 in bars. In the same figure type-approval and OBD threshold limits are shown as lines for reference.

Recapitulating what has already been discussed:

- NO_x and NO engine-out exhaust emissions of a vehicle were measured and used as input to an SCR model.
- The SCR model was optimized for US CARB certification and fixed at a performance level of 32 mg/km which is below the US certification limit of 43 mg/km (=70 mg/mile). (chart bar: FTP-75, NO_x control good)
- The SCR model was then modified to simulate SCR performance degradation increasing vehicle emissions to 77 mg/km which is at exactly the CARB OBD threshold limit of 76 mg/km (= 123 mg/mile = 1.75x70 mg/mile). (chart bar: FTP-75, NO_x control failed)
- The same vehicle with the same good SCR calibration was found to be compliant also to Euro 6 limits since it was simulated that it emits 24 mg/km over NEDC which is below the EU type-approval limit of 80 mg/km. This value was checked against market vehicles and found to be normal at the lower 7.2% of early Euro 6 vehicles. (chart bar: NEDC, NO_x control good).
- The same vehicle again run with the same bad SCR was simulated to emit 149 mg/km over NEDC which is slightly over the Euro 6 OBD threshold limit of 140 mg/km. The difference from the OTL is 6.4% < 20% which qualifies this failure for OBD type-approval.
- Similar vehicles according to data from US EPA / CARB are already certified in the US as able to detect this level of NO_x related malfunctions. Therefore, the OBD system of the simulated vehicle is expected to be able to detect the SCR degradation over any driving conditions. Since the simulated SCR malfunction covers the qualified deteriorated component definition of the EU OBD type-approval requirements, the vehicle is expected to be able to trigger a MIL illumination if driven with this level of malfunction over the EU OBD type-approval procedure.

Therefore, it is concluded that the latest vehicles certified by US EPA and CARB carry already OBD diagnostic technologies that can support the implementation of the Euro 6 NO_x OBD threshold limits.

4 Discussion on the findings

An assessment of the performance as regards PM and NOx OBD monitoring was performed in order to assess the transferability of monitoring technologies that allow compliance of US market vehicle with latest CARB OBD requirements to Euro 6 vehicles. The assessment was performed separately for PM and NOx as follows.

For the assessment of PM OBD thresholds a complete model was developed including the soot sensor in order to compare the performance of a accumulative soot sensor over FTP-75 with the performance over NEDC. It was found that the accumulative soot sensor can have a similar behaviour and can achieve at least one successful monitoring event, proving in this case that Euro 6 PM OTL is feasible.

For the assessment of NOx OBD thresholds a vehicle was modelled from driving dynamics down to the SCR system. Simulations demonstrated that a vehicle certified for stringent US OBD requirements can be also be considered a vehicle complying with Euro 6 NOx emissions and OBD thresholds with no modifications necessary either to increase or decrease the performance of the SCR. It was concluded thus that NOx monitoring technology already existing in US vehicles can be equally effective for vehicles to comply to Euro 6 NOx OTL.

The minimum engine capacity of the US certified vehicles used as pilot fleet was 2.1 l. Therefore the European vehicle that was simulated was selected to be within this engine capacity class (2.2 l). Since both NOx and soot emissions as well as exhaust flow and aftertreatment performance depend on engine capacity, all conclusions should be handled with caution for lower engine capacity vehicles. Since the vehicle fleet of USA does not include low engine capacity diesel vehicles, an assessment for this vehicle category was not possible.

As regards PM, two of the US certified vehicles of the pilot sample were certified with the same deficiency for PM monitor, not detecting a fault in a single FTP cycle. This means that there are cases where the soot sensor needs additional time for the completion of a monitor. In the assessment it was proven that similarly to the FTP-75 NEDC allows at least one successful completion of the PM monitor. Even better, in the case of a qualified deteriorated component for OBD type-approval pushed to 20% above OTL there are going to be even two successful monitoring events in the NEDC. Nevertheless, in order to allow as many sensing and OBD modelling technologies to be applied, an extension of the type-approval test to two driving cycles may also be considered. If applied in the OBD type-approval the two driving cycles should be run with no engine stop in between to allow more time for the completion of the sensor monitoring cycle.

Finally it needs to be stressed that all assessments were based on a limited vehicle sample, optimized to comply with the requirements of CARB legislation. OBD systems designed for EU fleet vehicles are expected to be further optimized using sensors at more advance development stage given the additional lead time to the next stage of Euro 6 OBD requirements.

5 Conclusions and Recommendations

Summarizing all findings, it can be concluded that:

- Besides the difference between US and EU legislation and type-approval procedures, the assessment revealed similarities in operation and OBD system performance and was possible to draw a safe comparison path.
- Existing technologies allow the implementation of OBD hardware and algorithms able to cope with the more stringent Euro 6 PM and NOx OBD requirements.
- Results were derived for vehicles belonging to the high engine capacity diesel engines in Europe.
- Cycle duration may be an issue for some vehicle manufacturers especially in the early stage of development.

In continuation of this project it is proposed to:

- Keep track of rapidly developing OBD sensing hardware and monitoring technologies.
- Perform testing on more advanced systems in order to assess the possible need for extending the duration of the type-approval cycle to two consecutive non-stop driving cycles.

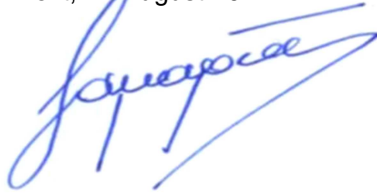
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7 Signature

Delft, 14 August 2014



Prof. Zissis Samaras
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