MODALES D2.2:
Real effectiveness of OBD inspection and maintenance, and retrofits

WORK PACKAGE	WP2: Knowledge of low-emission factors
TASK T2.2	OBD inspection and maintenance requirements
TASK T2.3	Retrofits
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Glossary of terms

EU Projects

Term	Description
UDRIVE	EU FP7 project (2012-2016) aiming to increase understanding of road user behaviour by systematically studying road user behaviour in real life conditions. First and foremost it focused on the identification of relevant measures to improve road safety up to the Horizon 2020 and beyond. Secondly, it focused on the identification of promising approaches for reducing harmful emissions and fuel consumption in order to make road traffic more sustainable.
uCARE	"You can also reduce emissions", EU H2020 RIA (GA 815002)
MODALES	This EU Horizon 2020 project: "Modify Drivers' behaviour to Adapt for Lower Emissions" (2019-2022, http://modales-project.eu)
ecoDriver	EU FP7 project (2011-2016) which addressed the need to consider the human element when encouraging "green" driving, as driver behaviour is a critical element in energy efficiency. The focus of the project was on technology working with the driver. The project delivered effective feedback to drivers on green driving by optimising the driver-powertrain-environment feedback loop.
The Auto-Oil II Programme	Final report, the Directorates General for Economic and Financial Affairs, Enterprise, Energy and Transport, Environment, Research, and Taxation and Customs Union with the support of the Joint Research Centre, 2000.
AUTOFORE	Study on the Future Options for Roadworthiness Enforcement in the European Union by The International Motor Vehicle Inspection Committee, known as 'CITA', in partnership with five research institutes. Received a 50% cost compensation from EC.
CITA 2002	Second CITA Programme on Emission Testing at Periodic and Other Inspections Programme Summary Report.
TEDDIE	TEDDIE - A new roadworthiness emission test for diesel, vehicles involving NO, NO_2 and PM measurements (by CITA)
Set I	Sustainable Emissions Test (by CITA)
Set II	Sustainable Emissions Test – Stage II (by CITA)

List of abbreviations and acronyms

Abbreviation/acronyms	Meaning
ACKN	Acknowledge
BRS	Bit Rate Switch
BS	Block Size
CAN	Controller Area Network
CAN FD	Controller Area Network Flexible Data-Rate
CBA	Cost Benefit Analysis
CF	Consecutive Frames
CI	Compression ignition (type of internal combustion engine)
CLD	Chemiluminescence Detector
CM	Conversion Method
CNG	Compressed Natural Gas
CRC	Cyclic Redundancy Check
CTS	Clear To Send
DALED	Mobile App for Low-Emission Driving
DA	Destination Address
DEL	Delimiter
DL	Data Length
DLC	Data Link Connector
DM	Diagnostic Messages
DoA	Description of Action (MODALES contract)
DP	Data Page
DTC	Diagnostic Trouble Code
EAT(S)	Emissions after-treatment - (system)
ECU	Electronic Control Unit
EDP	Extended Data Page
EOF	End of Frame
ESI	Error State Indicator
EPA	Environmental Protection Agency
EU	European Union
EOBD	European On-board Diagnostics (protocol), *see also OBD-II*
FDF	Flexible Data Rate Format
FF	First Frame
FMI	Failure Mode Identifier
FS	Flow Status
FSB	Fixed Stuff Bit
GDI	Gasoline (petrol) Direct Injection

Abbreviation/acronyms	Meaning
GE	Group Extension
GPF	Gasoline particulate filter (used in GDI-SI engines)
GPS	Global Positioning System
HD OBD	Type B variant of the OBD connector for heavy duty vehicles
IDE	Identifier Extension Bit
ICE	Internal Combustion Engine
I/M	[vehicle] Inspections and maintenance [programme]
LCC	Logical Link Control
LDV	Light-duty Vehicles (i.e. Passenger Cars)
LLSP	Laser Light Scattering Photometry
LNT	Lean NOx Trap
MAC	Media Access Control
MAF	Mass Air Flow
MDI	Medium Dependent Interface
MIL	Malfunction Indicator Light
NDIR	Non-Dispersive Infrared
NEE	Non-Exhaust Emissions
NOx	Nitrogen Oxides
NRMM	Non-Road Mobile Machinery
NSC	NOx Storage Catalyst
OBD	On-Board Diagnostics
OBD-I or **OBD 1**	On-Board Diagnostics, first revision (in U.S.)
OBD-II or **OBD 2**	On-Board Diagnostic, second revision (in U.S.), *see also EOBD*
OC	Occurrence Counter
OSI	Open Systems Interconnection (model)
PF	Protocol Data Unit Format
PID	Parameter ID
PGN	Parameter Group Number
PS	Protocol Data Unit Specific
PM	Particulate Matter
PM10	Particulate Matter of 10 Micrometres or Less in Diameter
PN	Particle Number
PTI	Periodic Technical Inspection
RRS	Remote Request Substitution
RSI	Road Side Inspection
RTR	Remote Transmission Request
SBC	Stuff Bit Counter

Abbreviation/acronyms	Meaning
SCR	Selective Catalytic Reduction
SF	Single Frame
SI	Spark ignition (type of internal combustion engine)
SID	Service ID
SOF	Start of Frame
SPN	Suspect Parameter Numbers
SRR	Substitute Remote Request
ST_{Min}	Minimum Separation Time
UDS	Unified Diagnostic Service
UNECE	The United Nations Economic Commission for Europe
U.S.	United States (of America)
VEIP	Vehicle Emissions Inspection Programme
VIN	Vehicle Identification Number
WWH-OBD	World-Wide Harmonized OBD

Executive Summary

This deliverable has three main themes that are addressed: 1) **detecting high-emitting vehicles with periodic tests**, 2) **probing the performance of Emissions after-treatment (EAT) system by on-board diagnostics (OBD)**, and 3) **assessing the potential of lowering the harmful emissions of vehicles by retrofitted EAT devices**. These three themes are supposed to reflect two tasks in the Work Package 2 (Knowledge of low-emission factors), namely "OBD inspection and maintenance requirements" (T2.2) and "Retrofits" (T2.3).

The literature review on the **effectiveness of inspection and maintenance (I/M) programmes**, particularly proliferated in the United States (US), showed that this type of activity was started in the 1990s, and is currently replicated to over 30 states. I/M programmes were deemed necessary, because exhaust emissions from motor vehicles were precursors for inferior ambient air quality, and thus the performance of the EAT system fitted to practically all vehicles since 1980 to curb the emissions needed constant status update to ensure the maintaining of their effectiveness. Separate programmes were necessary, because only a few US states had ever started a periodic technical inspection (PTI) programme for roadworthiness of the vehicles that could have been updated to include also emissions checks.

According to the review, a vehicle Inspections and Maintenance (I/M) programme is a compendium of different activities and procedures targeted to monitor vehicles' in-use emissions performance and reinstate the performance of any emissions after-treatment technology (EAT) systems fitted, if malfunctions are detected. The I/M programme is composed of a) procedures to gauge EAT performance; b) cut-points or other means of judgement to make a pass/fail decision; c) rules for reinstating the EAT performance and subsequent re-testing; e) vehicle categories and model years involved; and d) area of implementation. Historically, the emphasis in I/M has been on cars and other light-duty vehicles, but currently, there are also programmes embracing heavy-duty vehicles, as well.

Furthermore, the more detailed examination showed how there has been almost a constant evolution of the procedures used in probing the level of emissions, as well as an equally steady evolvement of the performance and complexity of the EAT systems. However, the enhanced complexity of the procedures and related hardware requirements add costs, and the review of some cost-benefit analyses revealed also testimonials suggesting that the cost-benefits or cost-effectiveness may not have been so good, and that the cost effectiveness of emissions inspection programmes has steadily declined over time.

In contrast to US, many European countries have a very long history and tradition for PTI of road vehicles for the purpose of ensuring their roadworthiness, thus increasing the safety of traffic by avoiding potential faults e.g. in brakes or other vital chassis systems. However, emission testing of road vehicles as part of a PTI has much shorter existence, as they were first introduced by some member states (MS) of the EU in the early 1980s. Furthermore, it was as late as in 1996 before the first consolidated roadworthiness Directive (96/96/EC) included the basic requirements for emissions checks needed to be implemented in all MS. As of today, systematic PTI activity is mandated in all EU MS with Directive 2014/45/EU, aiming at improving the quality of vehicle tests by setting common minimum standards for equipment, training of inspectors and assessment of deficiencies.

However, while assessing the **present characteristics and the progress of PTI procedures**, associated with the upholding of the roadworthiness of motor vehicles in Europe, plentiful and proficient literature on this subject attested that the present-day common PTI procure regarding checking of exhaust emissions remains highly inadequate. It does not address the need to evaluate in-use performance of the present-day EAT systems regarding crucial ambient air pollutants and precursors (NOx, PN). Also, amendments of PTI procedures are way behind the introduction rate of EATS in vehicles. Due to increasing stringency of the type approval (TA) requirements, more complex EATS are fitted to new cars and trucks to curb emissions, but current PTI does not address most of the critical features of their proper functioning at all. Thus, their continuous and effective operation is jeopardised, as the PTI cannot test their performance. Moreover, it was discovered that this issue is not technical but more of a legislative case, because according to the literature, several large scale studies have developed and presented procedures applicable to NOx and PM/PN emissions that could be implemented as parts of the PTI regulations, but the EC has failed to do so by today.

As a further option for identifying high emitters, **Remote Sensing Technologies** were also studied. Remote sensing device (RSD) measures an instantaneous emission rate of individual vehicles as they pass by the instrument location. It is not an exact measurement, but the results are rather expressed as emissions in g per g of fuel burned. Even if the first apparatus were successfully developed and used in the late 1980s, it has remained more as a tool to assess the assumptions of emissions factors in fleet emissions models such as MOBILE3 and MOBILE4, developed by U.S.EPA.

However, the technology has since taken substantial leaps, and is commercialised by several suppliers. Today, a fully functional remote sensing device (RSD) set-up has, in addition to a pollutant analyser, a camera device for linking the measured values to the vehicles license plate, and in some case even with additional vehicle data retrieved on-line OTA from a registration database using that license plate information. Furthermore, information of the acceleration of the vehicle during exhaust plume scanning is provided. The latest models add nitrogen dioxide (NO_2) to pollutants detected by the earlier device's nitrogen monoxide (NO), CO, carbon dioxide (CO_2), hydrocarbons (HC), and exhaust opacity.

Nevertheless, RSD data is not particularly good for assessing emissions of individual vehicles, but rather reflecting the characteristics of fleets. For these reasons, RSD can mainly be used for 1) Air quality monitoring and development of emissions models; 2) In-use surveillance to determine the average emission rates under real-driving conditions and assess the long-term durability of EAT systems, as well as 3) Vehicle inspection and maintenance, to detect if an individual vehicle has suspiciously high pollutant emissions in real driving, or, inversely, if this vehicle's after-treatment is well maintained, and thus can it be exempted from inspection.

Regarding **on-board diagnostics (OBD) and its features** the literature was searched for a review of the on-board diagnostics protocols that were found to exist in plentiful, differing in both hardware formats and software protocols. Since its early introduction in the 1980s by the California Air Resources Board (CARB), by 1988 OBD was implemented in all new cars complying with US emissions regulations. By definition, OBD is an electronic system that performs monitoring and diagnostics with regard to functioning of the exhaust emission relevant systems and components via an array of sensors and values they provide. Should these monitored values violate their pre-assigned ranges, an error case is determined, and its occurrence is signalled by a Malfunction Indicator Light (MIL), communicating to the driver that a system check should be performed. Furthermore, each identified error is additionally stored in a readable internal memory for later retrieval.

The next evolution of the system, OBD-II, was standardised in 1998, and later on it evolved also to become the European On-Board Diagnostics (EOBD) that was implemented in EU by 2001 (SI cars) and 2004 (CI cars). The functionality and performance of OBD-II and EOBD are fairly identical, and apart from assessing the status of the components vital for maintaining low emissions, additional information can be retrieved via OBD. These include e.g. oil temperature, vehicle speed, engine RPM, throttle position, airflow rate, fuel flow rate, coolant temperature and many more. Furthermore, identifying and diagnosing anomalous behaviours of systems and components can now be done by reading the Diagnostic Trouble Codes (DTCs) codes that are stored in the memory, hence allowing more specific determination of the main problem in the vehicle and EAT system.

This functionality and **list of parameters accessible via the EOBD interface is of the main interest in MODALES**. The intention is to use these functional parameters of the vehicle, engine and EAT system for the estimation of the vehicle's exhaust emissions level. Furthermore, they shall be used to characterise the driving, by attaching external data retrieval and storing device to a number of cars driven by volunteering motorists. To enable this, standards covering the physical hardware and software functionality of both the CAN bus and EOBD interface were examined. Additionally, the structure of the CAN messages was investigated, standard and extended identifiers were discovered, their meaning and priorities revealed, and finally, the Unified Diagnostic Service (UDS) standard necessary to interact with the array of vehicle ECUs was explored.

Aside the utilisation of the parameters to assess vehicle's emissions vs. driving characteristics, MODALES aims also to investigate the performance of EOBD to detect malfunctions and deteriorated performance of the EAT system. A simple EOBD functionality check and DTC retrieval could act as a substitute to physical measurement of harmful exhaust constituents. Furthermore, an improvement in the EOBD performance is also sought after, resulting in higher rate of detection in poorly maintained and/or tampered vehicles with elevated exhaust emissions. However, the literature review revealed critical flaws in present EOBD. It was found that the system is not robust enough, when it comes to tampering. Crucial defects in the current system are that DTCs can be easily cleared using readily available and low-cost communication tools, avoiding the entrapment in the PTI. Furthermore, new software can be loaded into the engine control unit (ECU) to increase engine power output and to disable EATS functionalities to alter the system in such a way that it avoids triggering of DTCs.

The last main theme, **potential impact of retrofitted EATS** was studied partly by a literature review, but more as a study of data retrieved from specific experiments performed for this very purpose, in order to assess, how different factors, environmental or mechanical, affect the function of retrofitted EATS. The data used in this analysis was collected by a NOx emissions monitoring system that collects live data from the vehicles with the retrofitted EAT system and uploads the information online to a back-office server. The "big data" retrieved for this purpose was collected from nearly 1700 buses, representing three configurations (solo, articulated and double-decker), and five different manufacturers. It was expected that an in-depth scrutiny of the collected data would reveal some phenomena that affect the EAT system operation negatively.

The analysis pointed out that vehicles with the smallest NOx emissions had slightly higher average speed than vehicles with the largest emissions. To illustrate the effect of driving speed to emissions, individual vehicle's emissions in relation to driving speed was studied. Furthermore, the study linked the exhaust gas temperatures and the efficiency of the EAT system, showing that high reduction rates need high exhaust gas temperatures, as AdBlue reactant cannot be injected, if the exhaust temperature is not high enough. Actually, higher average speeds were also found to attribute to higher load, and hence also elevated exhaust gas temperatures.

Retrofitting of passenger cars with SCR is possible and there are some approved systems on the marker. However, fragmented market and business to consumer -style business model sets limitations. It is difficult to justify retrofitting only by emission reductions, so other incentives like tax reliefs or subsidies are needed. Those instruments could also include parking permits, avoiding tolls and defying driving restrictions at low-emissions zones.

Regarding retrofits for non-road applications, the usage and installation varies a lot. This is setting higher cost for design and testing for approval. Retrofitting same engine, but installed in another application might require retesting and following possible in-use tests. This might raise the development and certification costs make retrofitting non-feasible. If the installed population is only few examples, statistical analysis of emission benefits is also difficult.

1 Introduction

1.1 Background

The impact of road traffic on local air quality is a major policy concern. There have been numerous technological advances and policy initiatives aimed at improving underlying vehicle and fuel technologies, reducing emissions through traffic management and seeking improvements through enforcement. Zero tailpipe emission technologies may solve the problem in the long term, as it is rolled out to the full vehicle population, but fleet renewal takes time. We need also to make more immediate changes, during periods in which road traffic continues to be dominated by internal combustion fleets (with its current share more than 95%).

However, such advances are hampered by a lack of understanding of the links between driving behaviour and emissions, and inconsistencies between laboratory tests and real-world emissions levels. A programme funded by the UK Department for Transport in 2016 showed that on-road emissions are significantly different from laboratory measurements. The study revealed that some cars emit up to 12 times the permitted EU maximum. Real-world emissions can be affected by many factors including vehicle characteristics, ambient temperature, traffic, road layout and driver behaviour. Recent studies have aimed to undertake large scale activity monitoring of engines to quantify these factors. Driver behaviour is regarded as the single biggest determinant of vehicle emissions.

The MODALES project was therefore created to advance the understanding of the co-variability of user behaviour and vehicular emissions, in particular from powertrains, brakes and tyres. From the understanding thus gleaned, the project aims to modify user behaviour via dedicated training, to help local and national authorities develop effective air quality plans and enforcement strategies. Over a 36-month timeframe, MODALES will study driving behavioural variability and recognise typical driving patterns and practises. Based upon that knowledge, it will establish the link between real vehicle emissions and driving behaviour through a combination of real-world measurement and laboratory tests.

Furthermore, MODALES will create training courses for low-emission driving, which will be taught and validated in pilot exercises. Poor maintenance and tampering aspects will be investigated with a fleet of cars whose emissions are intentionally influenced by lack of maintenance and/or by tampering, and MODALES will observe whether present On-Board Diagnostics (OBD) or inspections are able to detect those. Finally, an assessment of the potential impacts of retrofits for light- and heavy-duty road vehicles and for Non-Road Mobile Machinery (NRMM) will be performed, including promotion of their application in the selected pilot cities with relevant pollution problems.

1.2 Purpose and scope

WP2 is the technical kick-off activity for MODALES, aimed at synthesising the state-of-the-art in current international knowledge of vehicular emissions, in order to define key contributory factors. The factors considered vary from the driving and maintenance behaviour of individual car users, to the real effectiveness of OBD systems and retrofits, as well as assessing the legal situation of tampering in different member states.

The first deliverable of the WP2, D2.1 focused on the variability of driving behaviours and low-emission driving requirements, and the present deliverable focuses on three specific objectives of

WP2, namely the real effectiveness of OBD systems and retrofits. The third deliverable of this work package will be D2.3, dealing with the legal situation of tampering the vehicles' EAT systems.

1.3 Document structure

The three main subject matters of this deliverable are each addressed in their own chapters. At first there is a review of the I/M programmes and their effectiveness in Chapter 2, followed by a review of the OBD protocols in Chapter 3, and an assessment of the performance of OBD in detecting malfunctions in real-world use cases in Chapter 4. Finally, the third matter, the potential of retrofitting emissions after-treatment technology (EAT), is discussed in Chapter 5.

1.4 Deviations from the original Description of Action (DoA)

1.4.1 Description of work related to deliverable as given in the DoA

According to the DoA, this Deliverable at hand titled "Real effectiveness of OBD inspection and maintenance, and retrofits" should contain the following elements, carried out in Task 2.2:

- Review of inspection and maintenance practices within EU Member States and existing research literature across the world on the effectiveness of I/M to detect high emitting vehicles;
- Review of the OBD protocols and research literature on the performance of OBD in detecting malfunctions; and
- Investigation of the "inspection data base" in some countries in Europe such as Greece and order to identify the major issues in maintenance behaviour.

Furthermore, based on work in Task 2.3, it should also include the following topics:

- Analyse existing field data from retrofitted buses and trucks, real world emission reduction potential;
- Retrofit projects overview and analysis (technology requirements are different; some targets are less demanding than others); and
- Analyse which application is potential for retrofit and which is not. Average speed, vehicle type/base technology, vehicle age, etc.

1.4.2 Content deviations from the original DoA

Of the subjects in Task 2.2., the first two are covered by this Deliverable, but as regards investigations of the inspection databases, the work was decided to be incorporated and reported as part of WP4/Task 4.2. The decision was made mainly because the consortium was not able to gain access to suitable relevant databases within the timeline of preparing this Deliverable. In order not to delay this Deliverable any further, this part of work was decided to be transferred to Task 4.2, to be reported in D4.2.

Regarding Task 2.3, all the listed themes are incorporated in this Deliverable.

1.4.3 Time deviations from the original DoA

The finalisation of this document, which is a major piece of work in MODALES, and thus required several reviews and, as well as inputs from some industrial partners that were on reduced capacity due to the COVID-19 Pandemic situation. Furthermore, the Deliverable was originally scheduled in

Month 6, which turned out not to be realistic due to the fact that D2.1 was due in M7, and that deliverable needed to provide input into this one.

2 Review of the I/M programmes and their effectiveness

2.1 Background and definitions

A vehicle Inspections and Maintenance (I/M) programme is a compendium of different activities and procedures targeted to monitor vehicles' in-use emissions performance and reinstate, if necessary, the performance of any emissions after-treatment technology (EAT) systems fitted. It is composed of a) procedures to gauge EAT performance; b) cut-points or other means of judgement to make a pass/fail decision; c) rules for reinstating the EAT performance and subsequent re-testing; e) vehicle categories and model years involved; and d) area of implementation (EPA 2020a).

I/M programmes originate from United States, where they are now mandated on Federal level under the 1990 Amendment of the Clean Air Act for areas of poor air quality, mainly large metropolitan areas. Even before that, State of California enacted regulations asking a biennial "Smog Check" to be performed on most motor vehicles manufactured in 1976 or later. This programme was started in 1982 and is still running. The programme is a joint effort between the California Air Resources Board (CARB), the California Bureau of Automotive Repair (BAR), and the California Department of Motor Vehicles (DVM) (BAR 2020).

I/M programs have then proliferated and currently there are more than 30 U.S. states that have implemented an I/M program of some level (He & Jin 2017).

I/M programs were deemed necessary, because in US there is practically no wide-spread and systematic policy for periodic inspection of the roadworthiness and other safety-related performance attributes of motor vehicles. The matter is decided on state level, and only a few states ever started such safety-related inspection activities, and by today, most have abandoned them in recent years as being non cost-effective for preventing accidents (He & Jin 2017).

2.2 Summary of the Methodology

2.2.1 Light-duty vehicles

Light-duty vehicle I/M programs entail testing of vehicles' tailpipe and evaporative emissions for the purpose of determining the performance of the EAT systems fitted. Originally, in the early 1990's the testing was based on idle/high-idle measurement of tailpipe concentrations of pollutants (CO, HC). However, the more advanced programmes started using load-imposing tests, either as Acceleration Simulation Mode (ASM) that uses dynamometers to impose load on the engine while accelerating, or even more advanced procedure involving dynamometer test (IM240), which resembles a proper in-laboratory emissions measurement, but with a shorter (240 seconds) and simpler duty cycle. In these more advanced exercises, also NOx is measured. More details and current status of the procedures can be found in (EPA 2020).

After the widespread implementation of OBD-II systems in vehicles, checking the status and interrogating the OBD diagnostic trouble code (DTC) memory has been added to the procedures in I/M programs. Originally in 1996 EPA required OBD checks as part of an I/M programme from 1998, but eventually, the implementation was delayed until 2001 (EPA 1998). Furthermore, in many states, it has replaced dynamometer testing altogether for better cost-benefit ratio, and EPA's rules were amended to allow this (EPA 2001), but it is limited to vehicles of MY1996 or newer that have the OBD-II implemented.

Mostly these I/M programs are recurrent, i.e. all vehicles need to be tested periodically, and as a proof of passing the test, a window sticker is issued for the police to check. Typical testing interval is two years for vehicles younger than 6 years, and after that the tests become annual.

Testing vehicles taken directly from use for testing of their compliance with the I/M rules is an additional feature in enhanced I/M programs. In this activity vehicles are picked-up from the traffic and tested right at the site. Vehicle selection can be random or targeted, or a combination of both. Usually older vehicles are oversampled because of their greater potential to be high-emitters.

2.2.2 Heavy-duty vehicles

Whereas light-duty vehicles have been subject to inspection and maintenance programmes for several decades, specific programmes for heavy vehicles are fairly new. (Posada et.al. 2015)

2.2.2.1 The Heavy-Duty Vehicle Inspection Program (HDVIP) (CARB 2019)

The Heavy-Duty Vehicle Inspection Program (HDVIP) and the Periodic Smoke Inspection Program (PSIP) are CARB's heavy-duty vehicle inspection programs for in-use trucks and buses.

HDVIP consists of roadside testing by CARB enforcement personnel for excessive smoke, tampering, and Emission Control Label compliance, whereas the PSIP requires annual opacity self-testing for California fleets with two or more heavy-duty vehicles.

HDVIP requires heavy-duty trucks and buses to be inspected for excessive smoke, tampering, and engine certification label compliance. Any heavy-duty vehicle traveling in California may be inspected, including vehicles registered in other states and foreign countries. CARB inspection teams perform tests at border crossings, California Highway Patrol (CHP) weigh stations, fleet facilities, and randomly selected roadside locations. Owners of trucks and buses found in violation are subject to minimum penalties starting at $300 per violation. Penalty payment and proof of correction must be supplied to clear violations.

PSIP requires diesel and bus fleet owners to conduct annual smoke opacity inspections of their vehicles and repair those with excessive smoke emissions to ensure compliance. CARB randomly audits fleets, reviews maintenance and inspection records, and tests a representative sample of vehicles. All vehicles that do not pass the test must be repaired and retested.

2.3 Analysis of the U.S. programmes

2.3.1 Effectiveness of the programme to detect high-emitters

The effectiveness of the various U.S. programmes can be analysed at least from two different approaches. At first the implications that high-emitting vehicles have to the overall air pollution, and how much excess emissions would be avoided, if those vehicles would be eliminated, could be set aside, we can assess the basic ability of the programme to detect those high-emitters. Such an analysis was performed for the Californian Smog Check programme in 2008-2010, and reported in (Sierra 2009,). This analysis used the data from the actual programme, but also from supporting campaigns that were either ran parallel to the main programme, or explicitly launched to support this analysis.

Table 2-1: Summary of testing protocols for I/M programs (Source: ICCT, 2015)

Test Name	Loaded or Unloaded	HDV or LDV	Test requirements	Pollutant measured	Comments
Idle test and two-speed test	Unloaded	LDV	Roadside	CO and/or HC	Poor correlation with chassis test emission results.
Acceleration Simulation Mode (ASM)	Loaded	LDV	LDV chassis testing	HC, CO, and potentially NO_x	Improvement over unloaded test; strong correlation with certification testing results. Applies to vehicles with three-way catalytic converters but not OBD.
IM240	Loaded	LDV	LDV chassis	HC, CO, and NO_x	NO_x, CO, and HC emissions results correlate better with certification chassis testing than with the ASM. Requires a centralized program to amortize the costs.
MA31/BAR31	Loaded	LDV	LDV chassis	HC, CO, and NO_x	Shorter chassis-based test but has been deemed just as capable of high-emitter identification.
FAS or SAE J1667	Unloaded	HDV	Roadside	Smoke opacity	Designed for mechanically operated diesel vehicles. It is inadequate for PM screening or for measuring NO_x.
Lug-down	Loaded	LDDV and HDV	Chassis test	Smoke opacity	Targets older, smoky vehicles. Not designed for measuring PM or NO_x.
DT80	Loaded	HDV	Chassis test	PM, NO_x	The most comprehensive protocol among all HDV loaded I/M testing.

Note: LDDV: Light-duty diesel vehicles.

The longer-term parallel supporting campaign aside of the main programme was a Roadside Inspection Program, run by the Bureau of Automotive Repair (BAR 2000). From the very beginning this effort was targeted to evaluate the effectiveness of the main Smog Check programme, and it has been used to provide ongoing information regarding the emissions and compliance status of vehicles subject to the more enhanced Smog Check programme.

In this BAR activity, locations of the “pull aside” activities were first determined using a purpose-built site-selection tool to select areas that were suitable for this kind of activity. Main parameters in this process were size of the local fleet (over 1000 registered vehicles) and road network characteristics (only four-lane streets and max. speed limit of 45 mph). Then, in each of selected campaign locations vehicles were randomly selected using a stratified sampling protocol giving preference to older, higher emitting vehicles. Newer vehicles were deliberately under-sampled and older vehicles over-sampled relative to their distribution in the fleet. This mean that relatively few vehicles less than 10 years old were selected, and a disproportionately high number of vehicles more than 25 years old was selected.

Targeted vehicles were then pulled over and given on roadside a standard Smog Check inspection using portable dynamometers and analytical equipment to measure emissions using full-duration two-mode Acceleration Simulation Mode (ASM) test procedures. However, to reduce the test time, a few omissions and bypasses were in effect. Nonetheless, full Quality Control checks meeting or exceeding standard Smog Check program requirements were always made during roadside testing. These checks include calibration of the dynamometer and audit calibration of all gas analysers as prescribed in the main programme procedures.

For the reported analysis of the effectivity of the main programme, roadside data that was collected between February 2003 and April 2006 were used, and Figure 2-1 shows the distribution of number of tests in this batch to model year of the vehicles. Furthermore, Figure 2-2 plots the failure rates of both the roadside-tested fleet and the initial ASM tests. Based on the information in Figure 2, the report concludes that failure rates by model year observed in this dataset viewed against the initial test failure rates recorded in the Smog Check VID were generally about 1.5 times higher than the initial test failure rates seen in the programme for older vehicles. However, given the fact that the actual size of the older vehicle population and their contribution to the total VMT remains relatively small, this result is not very alarming, and does not contest the effectiveness of the Smog Check programme.

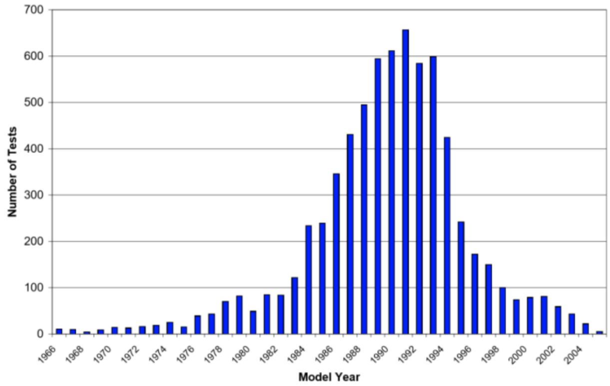


Figure 2-1: Distribution of Tests by Model Year in the Roadside Data *(Sierra 2009)*

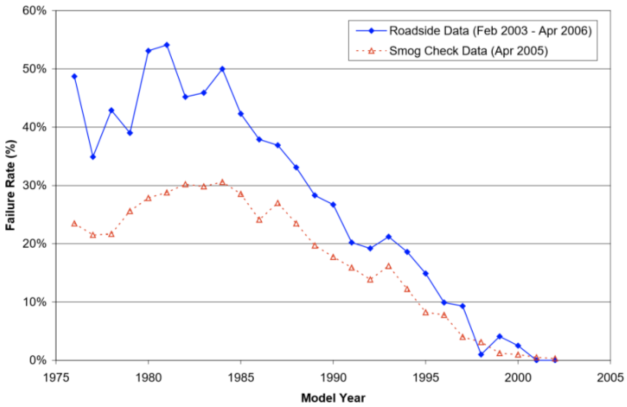


Figure 2-2: Roadside vs. Smog Check Program Initial Test ASM Failure Rates *(Sierra 2009)*

2.3.2 Cost-benefit Analysis or Cost-effectiveness Analysis

Another perspective for assessing the effectiveness of I/M programmes is associated with the benefits of catching high-emitting vehicles and how much excess emissions would be avoided, if those vehicles would be repaired or eliminated, and what the costs for running the programme are.

Over the years, there has been various Cost-Benefit Analysis (CBA) or Cost-Effectiveness Analysis (CEA). Even the original 1990 Amendment of the Clean Air Act included an *ex ante* cost-benefit analysis, and there has been numerous analyses published after the programmes have become widerspread. The following is a short summary of the findings of some of the more recent studies.

It has been well-established that I/M programs can **improve local air quality** by **reducing pollutant emissions** (CO, hydrocarbons) (Dehart-Davis, 2002), (Washburn, 2001), (Eisinger, 2005), and nitrogen oxide (Samoylov, 2013), and particulate matter levels, especially among pre-1985 model year vehicles (Sandler, 2017). Furthermore, I/M programs may **motivate pre-test repair work**, **improve repair**

effectiveness (Eisinger, 2005), and **create incentives for manufacturers to improve the emission characteristics of their vehicles**. This has been emphasised by Harrington 1997) and (Harrington, 2000), and it was claimed that this would reduce emissions more than the amount attributed to existing programs.

There is also evidence that **I/M programs with variable timing** and those **that target vehicles with a higher likelihood of being high polluters**, based on previous emission test results or attributes like odometer reading and vehicle age, engine size, **can be significantly more cost-effective** than regular, non-targeted annual or biennial retesting programs (Samoylov, 2013, Moghadam, 2010, Bin, 2003, Washburn, 2001). This is based on the fact that in a general, non-targeted program the costs of testing a large pool of vehicles are large, and if the testing can be more effectively targeted to vehicles that have higher than normal likelihood of failing the tests, testing costs are reduced. Furthermore, multiple inputs such as program participation rate, vehicle identification rate, and effective repair rate, should be included in thorough cost-benefit analysis (Li, 2017).

Furthermore (Samoylov, 2013) claimed that a **variable timing between tests**, i.e. vehicles with higher probability of failure to have more frequent testing, **would bring emission benefits** to be realised **from catching failing vehicles sooner**.

The same author (Samoylov, 2013) also argued that combining external, out-of-program data that was done outside of an emission inspection program, such as remote emission sensing, would more accurately model and describe, how vehicle's emission profile should be assembled.

On the other hand, **there are also testimonials that the benefits and the cost-benefits or cost-effectiveness may not have been so good**. (Harrington et al., 2000) shows that the costs of such programmes were higher than *ex ante* EPA estimates. More lately, (Sandler, 2017) showed that the **cost effectiveness of emissions inspection programmes has steadily declined over time**. This may be due to the fact that because of the legislation calling for longer warranted service life of the vehicles regarding exhaust emissions, the robustness of the EAT systems have increased, and thus the likelihood of the vehicle to become a high-emitter – no matter what – has been diminished. Furthermore, (Mérel et al., 2014) found evidence that a **significant amount of emissions abatement from repairs is lost by the time a subsequent inspection is required**. Therefore, the effect of VEIPs may be overestimated, if the judgement is made only on the basis of *ex ante/ex post* analysis of the emissions level of a failing vehicle, and the positive effects of the subsequent repairs.

Apart from assessing the cost-effectiveness or the cost-benefits of the programmes from the overall, societal perspective, there has lately also been **analysis from the societal equity point-of-view**. One of those is (Wessel, 2020) claiming that lower income individuals are more likely to drive vehicles that pollute more and are more likely to fail emissions inspections conditional on vehicle characteristics. Therefore, it is only fair that many of the programmes include elements like the maximum (tolerable) costs for rectifying non-compliant vehicles.

The state or federal intervention with the citizen's life in U.S. is traditionally strikingly different from the legacy and present situation in Europe, and especially in EU. In Europe and in EU, all citizens are treated quite equally to what comes of their social status and income level. However, many of the American I/M programmes include an entity called "waiver" (Harrington, 2007). It relates to a maximum monetary amount that was deemed acceptable to reinstate the performance of a vehicle that failed to pass an I/M test. The practice is the following: as the "M" in the abbreviation suggests, should a car fail in an I/M test, it is always sent to a licensed repair station for a diagnosis and estimate of a service and repair costs that were necessary to bring the vehicle to a status that it will pass the test. Furthermore, after such repair has been conducted, the vehicle is re-tested. However, should it still fail, there is a limit what is considered fair, and if all repair costs add up to exceed this limit, the vehicle receives a waiver, and it can be operated normally without any restrictions. This waiver is limited, though, for one vehicle and owner, and should the vehicle be sold, it does not free the next owner.

This maximum cost varies depending on the programme but is around 500 to 600 USD to gasoline-fuelled and about 1000 USD for diesel-fuelled vehicles. Furthermore, in some cases the owner of older vehicles may be eligible for cost compensation also from a separate CAP or other consumer programme (EPA, 2020).

2.4 Periodic technical inspections in European context

2.4.1 Background and short recapture of the past phases

In contrast to U.S. legacy, many European countries have a very long history and tradition for periodic inspection of road vehicles for the purpose of ensuring their roadworthiness, and thus increasing the safety of traffic by avoiding potential faults e.g. in brakes or other vital systems of a motor vehicle. However, emission testing of road vehicles as part of a PTI has much shorter existence, as they were first introduced by some member states (MS) of the EU in the early 1980s.Still , it was as late as in 1996 before the first consolidated roadworthiness Directive (96/96/EC) included the basic requirements for emissions checks, and thus they needed to be implemented in all MS.

According to (TEDDIE, 2012) these rudimentary emission checks first addressed petrol-fuelled cars only and included measurement of idle CO (and HC as an option), with cut-points for maximum contents. In addition to these criteria pollutants, the measurements entailed CO_2 to aid the determination of air-to-fuel ratio (a.k.a lambda). Furthermore, exhaust O_2 concentration was measured to detect excessive leaks in the exhaust system that could lead into dilution of the exhaust sample and thus falsification of the gas analyser readings.

Apart from CO and HC readings, the air-fuel ratio control was also checked. These measurements were done at idle and high idle, meaning that the engine speed was raised at least to 2000 rpm, to ascertain that the lambda-control that is essential for a TWC system performance is functioning as it should. Vehicle make/model-specific limit values established and communicated by the manufacturers were favoured, but there were also global limit values, usually more lenient, to be used in the absence of the information on specific limit values. Gas analysers used in this context for CO/CO_2 and HC were of NDIR type, and of the same type that are commonly used in garages and repair shops for check and tune-up of the cars during maintenance operations.

For diesel engines these first stage emissions checks were based on measuring the opacity of the exhaust gases with an opacimeter in a ‘free acceleration smoke’ (FAS) test. In a FAS test the engine is rapidly accelerated (with clutch disengaged and gear in neutral position) from idle up to the point that the speed limiter cuts off fuelling. Thus, the engine’s internal inertia is entertained for the purpose of establishing some load, and hence to produce a more relevant and representative transient operating sequence that better corresponds to real driving situations. Usually a few of these short accelerations are performed, and an average of the readings is calculated. Also here, a vehicle make/model-specific limit values are favoured, usually communicated via a plate affixed to the engine, but also global not-to-exceed limit values are in use.

The technical requirements of apparatus for measuring the opacity of exhaust gas are defined in the international standard ISO 11614:1999. The weak point of the FAS test is that when measuring smoke opacity, a surrogate value to the real nuisance being (fine) particulate emissions is used, and there is no consistent correlation between results of a FAS test and actual PM measured from the same engine.

2.4.2 Present status

Today, systematic PTI activity is now mandated in all EU MS with Directive 2014/45/EU (EU 2014a), improving the quality of vehicle tests by setting common minimum standards for equipment, training of inspectors and assessment of deficiencies. This Directive is supplemented with Directive 2014/47/EU (EU 2014b) on technical roadside inspections (RSI) for commercial vehicles.

These directives are stemming from the Commission, which on 20 July 2010, adopted policy orientations in which it announced a) the harmonisation and progressive strengthening of EU legislation on roadworthiness tests and b) on technical roadside inspections; c) the inclusion of powered-two wheelers in vehicle inspections; and d) the possible setting-up of a European electronic platform with a view to harmonise and to exchange vehicle data.

This was deemed necessary, because in the impact assessment (EC, 2012) of this legislation, it was concluded that in Europe, technical defects contribute heavily to accidents: it is estimated that they are responsible for 6% of all accidents, translating into 2,000 fatalities and many more injuries yearly.

Furthermore, technical defects cause environmental damage, as according to a CITA report (AUTOFORE, 2007) an increase in emissions (e.g. CO, HC, NO and CO_2) by some 1.2% and 5.7% on average, has been detected. However, those can be by up to 20 times for particular vehicles, and these "gross-emitters" are of particular concern and should be removed from operation as soon as possible for repair or write-off, if the repair actions fail. This was already found in the European Auto Oli II programme (Auto-Oil, 2000) that reported with regard to three-way catalyst equipped vehicles (TWC), a properly operating inspection program for TWC cars could have the potential to reduce emissions in the order of 35% for CO, 25% for HC and 5% for NOx, Furthermore, with regard to non-catalyst and oxidation catalyst equipped vehicles, such an inspection program would have the potential to achieve a 15% reduction in CO emissions; and with regard to Diesel vehicles, the emission reduction potential is about 25% in particulate matter (PM). However, it is fair to note that these findings are now more than 20 years old, and thus current situation may be somewhat different.

Nonetheless, detecting and eliminating the "gross emitters" is the other main operational objective of the Roadworthiness package, and thus additions to the minimum requirements of both PTI and RSI were introduced. In the impact assessment (EC, 2012), there were different policy options (PO, i.e. combinations of measures) studied, and they concluded, based on the analysis of avoided emissions and their cost-equivalent monetary savings that

2.4.3 Suggested improvements for periodic technical inspection by joint projects

The first large-scale multi-partner study to address Inspection and Maintenance in the European context as a means of improving the emissions performance of the in-use fleet was the Auto-Oil II programme. Especially its WG3 addressed this theme as part of periodic technical inspection (PTI). It sought means and ways to enhance what was recently laid out in the first consolidated roadworthiness Directive (96/96/EC) that included the first set of basic requirements for emissions checks.

One of its conclusions that still stands out was: “A properly operating inspection and maintenance programme is of crucial importance in order to ensure that expected emission reductions are realised in practice, and could have the potential to bring about some additional reductions in emissions at the time of introduction, but emission reductions will decrease over time as newer vehicles replace older ones”. (AO-II, 2000)

This study paved the future framework for private-public-partnership type of approach in studying vehicle emissions, and for the further improvement of the PTI in Europe in view of better detection of high-emitting and tampered vehicles, there has been as series of coordinated research initiatives, co-funded by the European Commission, executed under the leadership of CITA (International Motor Vehicle Inspection Committee). These are shortly here summarised in chronological order, with a description of their focus and a set of main findings and/or recommendations.

2.4.3.1 2nd CITA Emission Study (CITA 2002)

The first International Motor Inspection Committee (CITA) study was mostly concentrated on the FAS-test for diesel engines, whereas the second study was more focused on petrol-fuelled vehicles. This programme consisted of five sub-studies:

a. a working group to consider a ‘best practice’ procedure for measuring exhaust emissions from petrol vehicles
b. a study on motorcycle exhaust emissions and noise
c. a study on the use of OBD during periodic inspection
d. a study on the influence of catalyst temperature on the effectiveness of periodic inspection
e. a study to examine the feasibility of a large-scale data gathering exercise.

Some of the main findings of this study were that no further elaboration of emission checks for pre-OBD vehicle generations (i.e. older than EURO 3) is necessary, as there will not be sufficient returns for the time and effort required. Furthermore, these vehicle generations are now 20 years or older, and their share of traffic work is quickly diminishing. On the other hand, the study saw great opportunities in combining an OBD check and tailpipe emissions test. However, an urgent need for improved uniformity in the interpretation of the OBD type approval requirements was seen. This was manifested by the fact that significant numbers of current cars tested in this study with OBD did not comply with the applicable type approval limits.

In addition, as a general conclusion, the study suggested that the type approval directives for noise and emissions should take more account of the needs of in-use enforcement, particularly the requirements of periodic inspection.

2.4.3.2 TEDDIE (TEst (D) DIEsel) Project (CITA 2011)

TEDDIE was a one-year project funded by the DG MOVE. Its overall objective was to define new test procedures and equipment for measuring emissions of nitric oxide (NO), nitrogen dioxide (NO_2) and particulate matter (PM) from diesel vehicles during periodic technical inspection (PTI).

In this study several preliminary recommendations were identified for consideration in relation to the legislation and improving the effectiveness of the PTI included the following ones:

a) The free acceleration test (FAS) remains a suitable procedure for modern diesel cars. However, consideration should be given to how the functioning of the engine speed limiters can be ascertained so that the free acceleration test can be conducted for all vehicles without damages.

b) In the current legislation the diesel emission limits are stated as "k" values in m^{-1}, which are the units of opacimeters. Consideration should be given to a changeover to the measurement of the mass concentration of PM (in mg/m^3) for new vehicles meeting a specific emission standard.
c) With this changeover, the legislation would need to make an allowance for the use of appropriate PM-measurement devices (such as LLSP instruments). There would also be a need to define a correlation between PM values in mg/m^3 and k values in m^{-1} to be used in the devices.
d) General limit values for PM (or any adjustments to plate values) should be based on the findings of field trials.
e) Pending the results of further studies, the extension of the use of OBD in the legislation should be considered for the evaluation of components and individual systems emissions and other parameters, which are relevant to PTI tests (e.g. engine speed) as a supplementary part of the emission data

2.4.3.3 CITA SET I – Sustainable Emissions Test (CITA 2015)

This project was a follow-up on the TEDDIE study and was acknowledging the latest developments in vehicle and measurement technology. With more stringent type-approval limits in-force (Euro 5 and Euro 6), after-treatment systems such as exhaust gas recirculation (EGR), diesel particulate filters (DPFs), selective catalytic reduction (SCR) have become necessary. Also, use of on-board diagnostic (OBD) is more widespread. Both petrol and diesel-fuelled vehicles were addressed in M_1 and N_1 categories.

This project concluded that there is no clear correlation between an emissions test and OBD check for either petrol or diesel vehicles. Therefore, it is recommended that for Euro 4 or later vehicles, both an emission test and an OBD check should be performed.

Furthermore, regarding petrol vehicles the limit values (cut-points) should be addressed, as follows:

a) for Euro 3 vehicles, the current limit is suitable;
b) for Euro 4 or later vehicles, a revised limit of 0.1% CO should be used for the fast idle test, and even a stricter of limit of 0.05% CO could be introduced for Euro 4 or later vehicles, but some Member States might require new equipment to test to this level;
c) the current limit is suitable for the normal idle test

In addition, for diesel vehicles the study summarised:

- a) for Euro 3 vehicles, the current limit is suitable
- b) for Euro 4 vehicles, because some are fitted with DPFs whereas others are not, the limit should be the plate value, but maximum 1.0 m^{-1}
- c) for Euro 5 or later vehicles (all with DPF), a general and stricter limit is practical to apply. It is recommended that a limit of 0.2 m^{-1} will be used

Regarding OBD, there were several findings, such as

a) During the OBD test, any vehicles with a "P0…" DTC should fail the test. Some trouble codes might only affect cold-start emissions (e.g. glow plug function) which would not show up in a free acceleration test. But it is still important that these vehicles are rectified to avoid excessive cold start emissions
b) Introduction of a combination of OBD scanning and tailpipe concentration measurement will have the best benefit and ability to find most of the emission behaviour affecting failures on modern passenger cars
c) The use of OBD will also provide additional information useful for the correct execution of the emissions test for both petrol and diesel vehicles. These supplemental parameters include e.g.

engine coolant temperature and engine speed. As for diesel vehicles, also the following parameters should also be recorded and evaluated: maximum engine speed and rising time (during FAS test)

2.4.3.4 CITA SET II - Sustainable Emission Test for diesel vehicles involving NOx measurements (CITA 2019)

This study remains as the latest in this series of coordinated and collaborated efforts of the testing and inspection industry, as well as the scientific community regarding vehicle emissions and their measurement technologies related to in-use compliance checking and performance assessment.

The goal of this study was set to develop new methods for inspection of the levels of emissions of nitrogen oxides (NO_x) from M_1/N_1 diesel vehicles <3.5 ton, suitable for use in regulatory purposes and to be used in Periodic Technical Inspections (PTI). These methods should assess NO_x EAT performance to ensure that the system is functioning correctly, be cost efficient and practical to implement in the current PTI regime.

In general, the study accomplished that:

1) Test methods with load simulation show a good potential to detect emission related failures: the ratio between concentration values between vehicles that pass and fail is high (up to 4)
2) The test methods without load simulation show lower ratios (less than two) between vehicles that pass or fail.

A further observation wat that high idle and FAS tests are sometimes not possible because of the limitation of the cut-off speed.

Furthermore:

3) Conditioning is important for a robust result of an emission test. Especially in SCR systems the catalyst temperature is very significant for the level of NO_X-concentration and the efficiency of the system in general.
4) Thus, it is important to have information regarding the complete EAT system as well as the software strategy and its function to evaluate possible interaction of several installed systems;
5) Different EAT systems can interact and compensate for a defect in a different system.

These findings brought the study to the following conclusions:

a) To be able to effectively evaluate the NOx-behaviour of diesel engine EAT systems, there is a need for specific technical information for the vehicle, of its
- EAT system(s) installed;
- Software strategy (mode of operation);
- Sensor information, which already exists in most of the OBD systems like SCR temperature, urea injection rate, EGR valve activity or NOx values in a standardised way

b) Preconditioning of the vehicle is crucial for a valid test result;
c) Loaded tests are more meaningful than unloaded tests;
d) The combination of comprehensive OBD-information and real emission tests are necessary for a proper evaluation;
e) The tests conducted emphasise the complexity of NOx measurement in practice;
f) Further tests are required to give confidence in the initial results.

For setting the limit values or thresholds for FAIL/PASS, a reference value for a fully functioning EAT ought to be defined as part of the type approval of the future vehicles. This kind of approach was already suggested in the previous phase (SET I). Furthermore, **for older vehicles a representative sample of vehicles in circulation should be tested to come up with acceptable cut-points**. In addition, the **study suggested to assess the potential of short trip tests, as well as the use of measurement sensors which are used on vehicles**, e.g. within a so called MINI PEMS test.

As a part of the study, **a cost benefit analysis (CBA) was performed on the proposed test procedures.** The test procedures considered differ in terms of costs and accuracy of emission measurement. However, **with more elaborate and accurate procedures, more high emitting vehicles should be entrapped with higher benefits for air quality improvements.** The CBA was based on the time taken to perform the tests and the amount of additional faulty vehicles detected and repaired. The more sophisticated loaded tests with more accurate equipment had highest return rates, and the unloaded somewhat lower. However, this assessment also found that benefit-cost ratio's (BCR's) decrease over time, because the total amount of diesel vehicles decreases over the investigation period. Nevertheless, the analysis showed that the **benefit-cost ratios are excellent for all investigated test procedures over the time period of next 10 years**.

Finally, the **study concluded that further investigations were still needed**. Therefore, the study recommended taking the following points for consideration in the next NO_x emission study related to PTI:

a) Further tests are required in order to a) to define thresholds; b) to get better understanding of the behaviour of EAT systems, and c) to elaborate practical procedures for PTI emission tests;
b) Short test drive as an alternative seems promising, but needs further investigation;
c) Further tests should include an extended OBD-reading (diagnostic tool) and vehicle-specific information provided by the OEM;
d) Specific reference values for periodic emission tests should be defined at the time of type approval (Euro 6 and further) for future vehicles;
e) It seems appropriate to combine the loaded ASM2050 method with the unloaded test method for EGR assessment and OBD – read out for better evaluation;
f) Coordinated EU-wide approach is necessary.

2.4.4 Other relevant studies

One of the shortcomings of the present PTI is that it is not worthwhile to measure NOx, even if it is the other main precursor (together with PM/PN) for low air quality, because without load, the levels of NOx emissions remain inherently low. Using a chassis dynamometer - like in many enhanced US I/M programmes - would facilitate more proper evaluation of the NOx emissions performance, but high costs are an inevitable consequence. To evade high costs, low-cost alternatives have been studied, and (Latham, 2007) gives one example of such a set-up.

This project focused on the development of a new type of dynamometer for measuring exhaust emissions from light-duty vehicles, which is cheap and relatively easy to use, but can simulate load condition typical for real driving situations. A prototype was developed and tested using three cars, two petrol and one diesel. The system utilises free running chassis rollers and uses vehicle brakes to apply load to the engine. Exhaust concentrations were measured with typical PTI station (or repair garage) equipment and combined with readout of OBD data to allow approximated mass emissions calculations.

The outcome of this work showed the eventual potential of this kind of set-up, but the limited test vehicle set was not large enough to ascertain the full usability of such a set-up.

2.4.5 PM and PN emissions measurements in PTI

Apart from NO_x, mass of (all) particulates (PM) or number of (very small) particulates remains an issue regarding local air quality in many European cities. For the purpose of addressing this issue, type approval requirements has been amended to first encompass a PM limit value (EURO 5), and more recently a PN limit value (EURO 6). Both are imposed on CI and SI engines, but for the latter engine type only with GDI (direct-injection) fuel delivery/combustion principle, as the traditional *ex-chamber* port-fuel injection does not induce (any size) particulate formation and emissions like the *in-chamber* injection and subsequent combustion.

However, GDI is needed for best efficiency. To avoid this phenomena, some manufacturers have adopted dual injection strategy, and are using port or GDI-injection depending on the operating point (speed, torque) of the engine, as the propensity of the GDI combustion to generate particulate emissions is limited only to specific parts of the operating map, Therefore, the use of the port-type injection will be limited to those areas only, and GDI injection is used elsewhere for better fuel efficiency.

Furthermore, there are many papers published addressing the subject of how to check PM and PN emissions in terms of PTI. The most numerous of these studies has been initiated and funded by *the Dutch Ministry of Infrastructure and the Environment* that has funded several studies in this respect, addressing both light-duty and heavy-duty classes. (Kadijk 2015), (Kadijk et al. 2015), Ligterink et al. 2016), (Kadijk et al. 2016), (Spreen et al. 2016), (Kadijk et al. 2017a), Kadijk et al. 2017b)

In (Kadijk 2015) an investigation was made on the possibilities of detecting the filtration efficiency of DPFs, including impaired or totally abolished units with tampered OBD-systems, with instrumentation and procedures that could be implemented as part of the PTI. The methodology was to use smoke meters with different sensitivity and a sample of DPF units with different filtration efficiency.

A set of similar DPF cores were treated by artificially “opening” of a number of plugs in the filter core to let part of the exhaust gases flow directly thru the channels, and not thru the porous wall structure of the core. The modified filters were targeted to different levels regarding the type approval limits, and when mounted on a test vehicle, represented different PM emissions and filtration efficiencies. Figure 3 portrays a summary of measurement results for those filters, showing the reasonably good correlation between PM, PN and smoke measurement results.

As main result, the study concluded that smoke tests are suitable for roadworthiness tests of diesel vehicles with diesel particulate filters. However, the smoke test equipment must be able to measure low smoke emissions accurately. Measurement range of a state-of-art opacimeter of 0 – 3.0 m^{-1} should give satisfactory results, as typical levels of smoke in FAS test with Euro 5 engines without DPF is 0.20 to 0.40 m^{-1}, i.e. about 10 % of the total range of the instrument, whereas common standard opacity meters with ranges up to 10 m^{-1} are not sensitive enough.

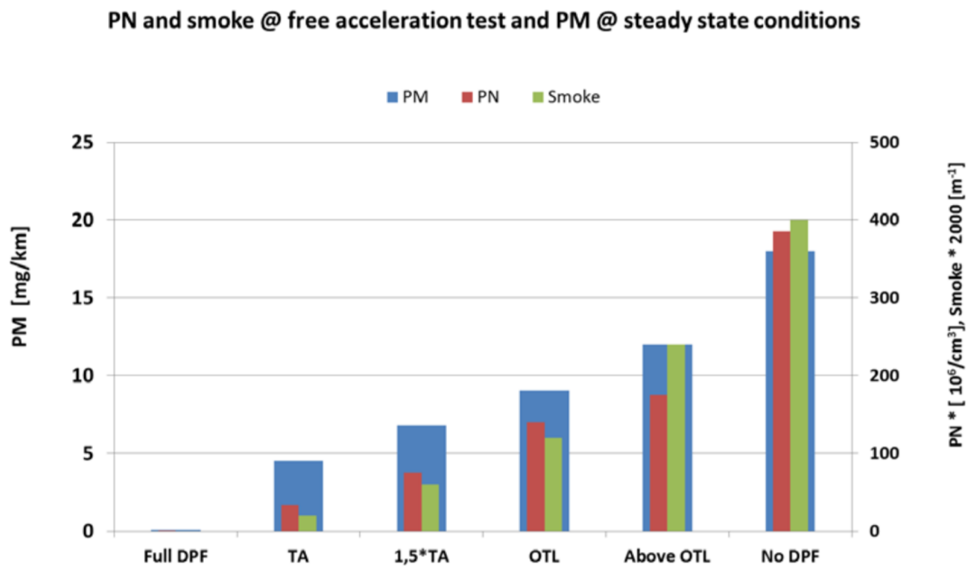


Figure 2-3: Resulting PM, PN and smoke emissions in FAS test with different levels of impairment of the DPF unit *(Source: Kadijk 2015*)

The work was continued and reported by (Spreen et al.,2016). In that study those two smoke meters were used, but also a condensation particle counter (CPC) instrument was available as a supplement. In this phase altogether 213 passenger cars and light-duty vehicles were tested using various different methods ranging from swipe test (with a clean finger) inside the tailpipe to idle measurement of PN at idle, and normal FAS test in between. For vehicles that showed abnormal results in any of these tests were tested also with a tissue filter test, where a tissue was attached to cover the tailpipe exit and the vehicle was let to idle for three minutes. Tissues were visually checked for levels of blackening and other colouration and photographed for the reference record. Figures 2-4, 2-5, and 2-6 show results for those vehicles tested.

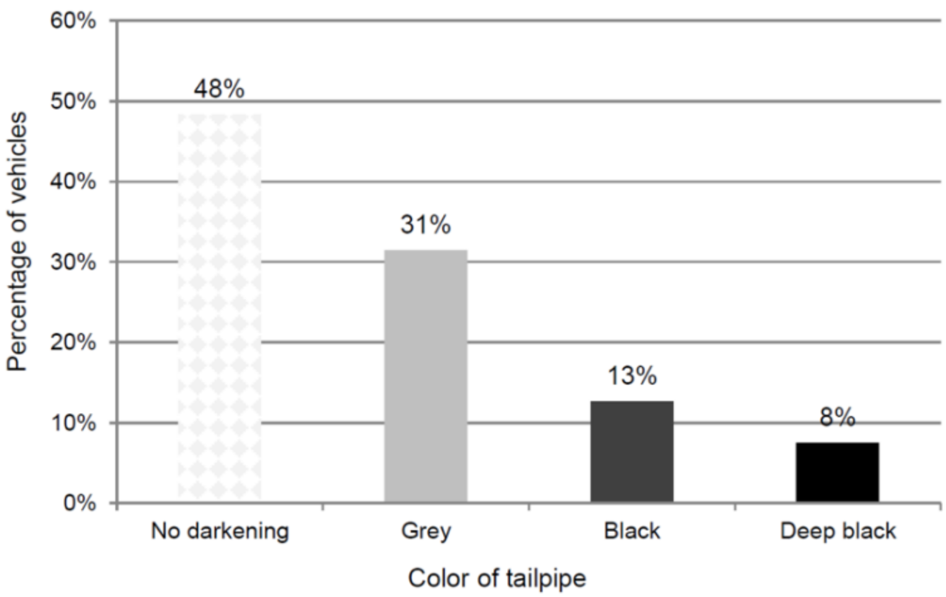


Figure 2-4: Results of the tailpipe sweep test *(Source: Spreen et al., 2016)*

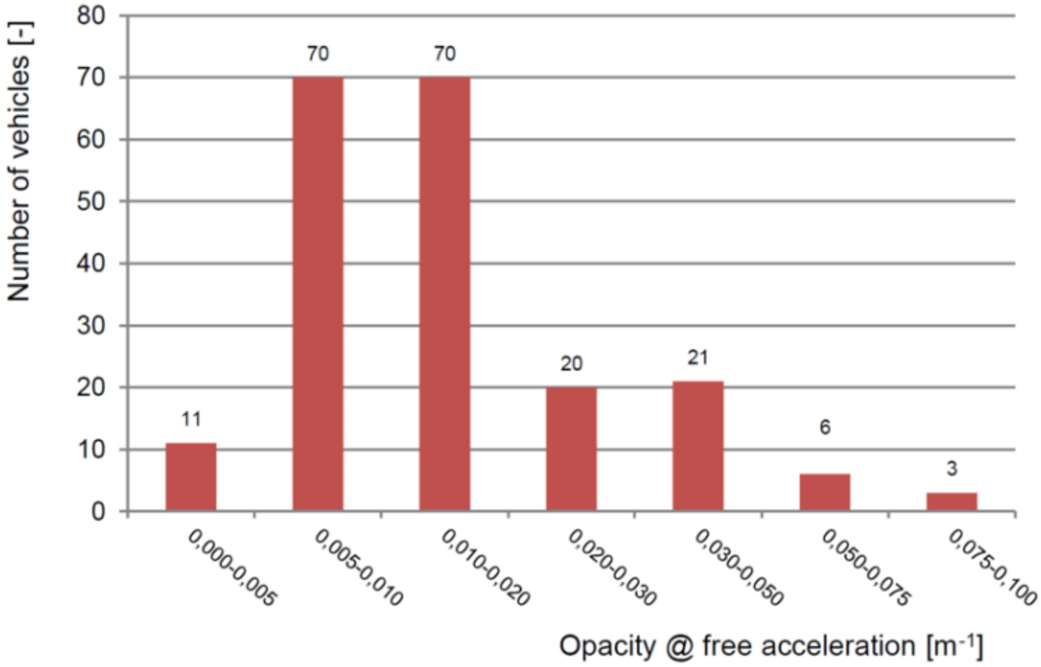


Figure 2-5: Further analysis of the 201 vehicles that did not exceed 0,10 m-1 using the improved opacity *(Source: Spreen et al., 2016)*

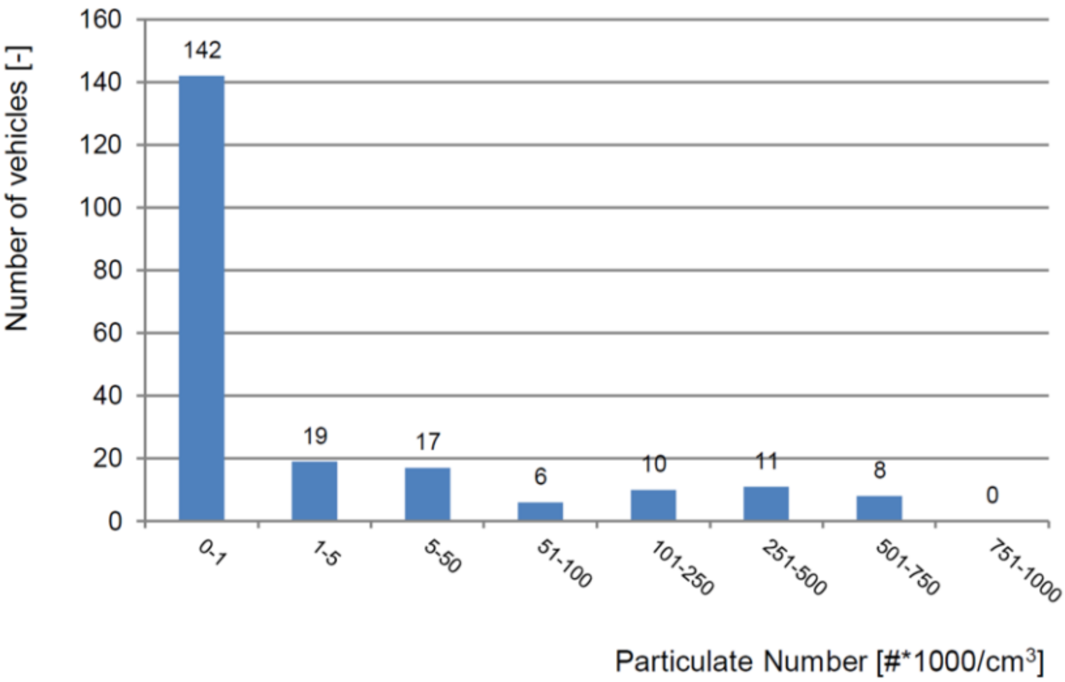


Figure 2-6: Particulate emission test results measured in low idle speed tests *(Source: Spreen et al., 2016)*

The latest piece of this study is (Kadijk et al. 2017), where 14 light-duty vehicles (10 diesel, 4 petrol, Euro 3, Euro 4, Euro 5, Euro 6) were tested using various different procedures and instruments, including the usual FAS test with opacimeters (normal, and more sensitive), idle test with four different particulate number (PN) meters, as well as full in-lab chassis dynamometer tests to establish the level of emissions for these vehicles in statutory tests. In these in-lab tests different fuel grades were also used, as it is known that use of paraffinic (GTL) diesel fuel can lower exhaust smoke over standard EN590 grade, and thus could create an escape route for at least a marginal high emitter.

As an example of the results, results of in-lab dyno test PN and idle test PN are presented in Figure 2-7, for two vehicles that had cracked filters and for one that had a DPF with adjustable bypass to vary filtration efficiency and PN emissions level. Correlation between the results of the full-scale dyno test and the short idle test is quite good. However, the correlation between in-lab PM and PN at idle is less favourable, as one can see in Figure 2-8 that depicts such results.

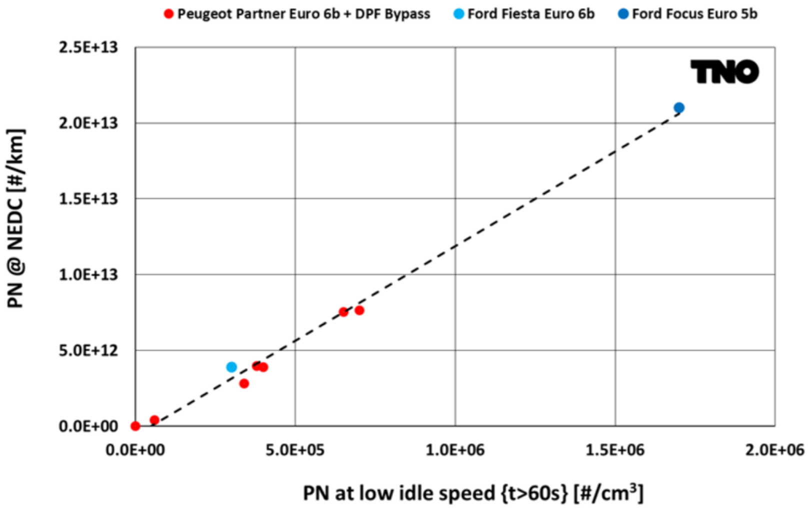


Figure 2-7: PN emission results measured in low idle speed tests and on chassis dynamometer *(Source: Kadijk et al. 2017)*

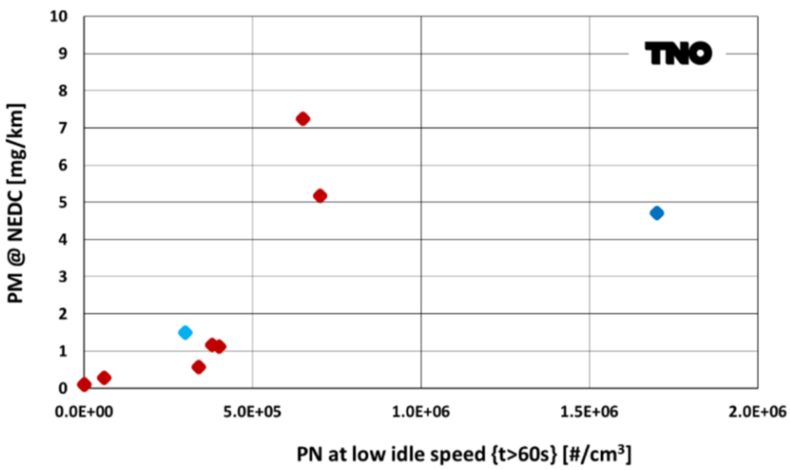


Figure 2-8: Low idle PN and PM measured on a chassis dynamometer *(Source: Kadijk et al., 2017)*

The study concluded that PN emissions test on low idle with a hot DPF is suitable for PTI purposes, but for older vehicles without DPF, the current FAS test is recommended. However, the available mobile PN testers are too expensive for most PTI stations, but work has been initiated and development of a PTI-PN tester is on-going. Moreover, it has already been found that the new PTI-PN tester does not work with petrol-fuelled vehicles, as their exhaust composition deviates so strongly from that of diesel-fuelled. This remains an unsolved issue, because modern Euro 6c petrol cars are subject to strict PN limit values, and employ filters similar to those in diesel vehicles. This will also suggest that in near future, those vehicles need similar control measures as diesels.

Finally, the study settled that current EOBD is not able to sufficiently judge failures in DPF, because it has no PM or PN sensor, and the OBD system is susceptible against tampering and re-programming with inadequate safeguards for these.

2.4.6 In-Use compliance of heavy-duty diesel trucks and PTI

The Dutch Ministry of the Environment and Infrastructure has also contracted research on in-use emissions and compliance of heavy-duty diesel trucks (Riemersma et al. 2000), (Riemersma et al. 2009), and most recently (Vermeulen et al. 2016). Based on that experience, the research party has addressed also issues related to PTI, or more specifically measuring NOx emissions in roadside inspections, in (Vermeulen et al. 2012). For this purpose, a smart emission measurement system (SEMS) has been developed, which is able to screen the emission performance of heavy-duty vehicles, while driving a short real-world trip on the road. The method is based on an automotive NOx&O_2 sensor and is combined with a GPS and data acquisition to gather data about the speed profile of the vehicle during the test trip. As such, the authors claim that the method is a valid tool to check the NOx emissions in an effective, robust, relatively cheap way.

2.4.7 On-board sensing of particulates and OBD

Parallel to the efforts of developing more effective measures for application in PTI, recent studies, such as (Rostedt et.al., 2009), (Bilby et al. ,2016), (Stavros et al., 2016), (Rostedt et al., 2017), (Maricq & Bilby, 2018), (Kontses et al., 2019), (Boveroux et al., 2019), (Burtscher et al., 2019), have also addressed the issue of high PM and PN emissions via assessment of various technologies and their potentials for direct, on-board sensing of high particulate emissions and inclusion of this signal to the overall scope of OBD. Sensor technologies that have been evaluated include different electrical charge-based and electrical detection, as well as optical methods.

2.4.8 Using inspection data base to identify major reasons for failure

With access to a database of failure reasons of PTI tests could give a possibility to evaluate the rate of performance shortcomings that are most commonly leading to a fail in the inspection. An example of such data and output is depicted in Fig. 2-9, based on data from Dutch technical inspections having taken place in 2006.

The Figure shows that the failure rate is at the highest amongst cars of 14 to 15 years of age. Furthermore, we can see that exceeding the emissions cut-points is the fourth largest cause of failing the inspection, and the highest rates for emissions are acquired at 13 and 14 years of age.

However, we may also argue that because of the EOBD system fitted to almost all cars now over 15 years of age, impairs this statistical approach, because if the vehicle in question has an emissions-related fault, OBD renders a DTC and lights-up the MIL-light. Therefore, the motorist is duly alerted of a problem related to emissions, and most probably rectifies the problem before taking the PTI test. Therefore, failures because if excessive emissions in vehicles that do have a fully functioning

EOBD, should be considered as an evidence and testimonial of the inability of the present EOBD to duly flag high emitting vehicles as it should.

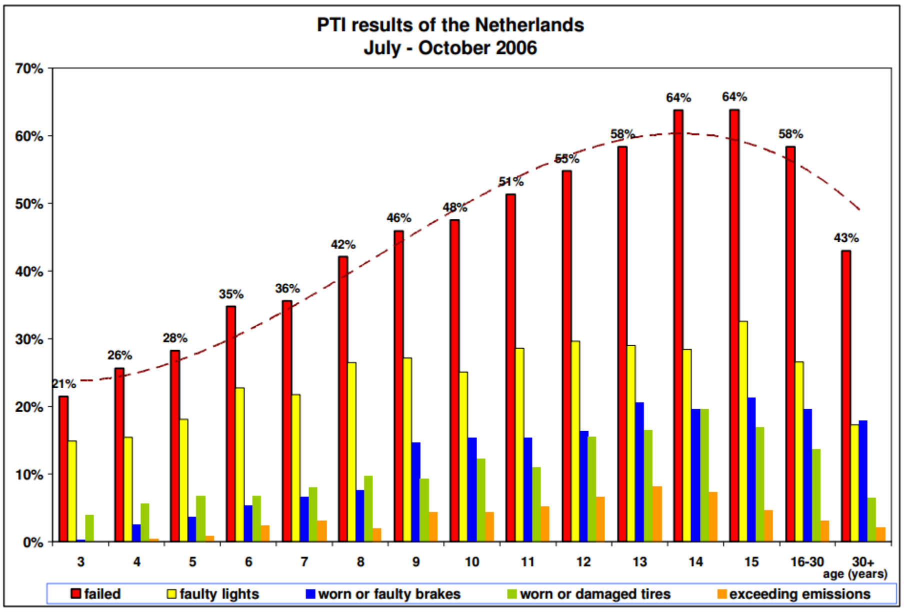


Figure 2-9: Inspection failure rates for different ages of light vehicles for the Netherlands over a 4-month period in 2006 *(Source: CITA, 2007)*

2.5 Summary and Conclusions on I/M & PTI

We may definitely say that United States has clearly led to path to effectively regulate and curb exhaust emissions from motor vehicles. The U.S. EPA has long ago developed the basic set-up of a three-stage approach for regulating the exhaust emissions form motor cars. The first stage is the Type Approval (TA) that has maximum permissible amounts for different pollutants that a vehicle can emit, when tested in a laboratory according to several different test procedures. The second stage applies to in-use vehicles, and is called "in service conformity", (ISC). In this phase several vehicle families are tested annually, to determine, if their emissions remain below legal limits. If malfunctions are found on these "properly maintained" vehicles, a recall may be issued, and all vehicles of that type needs to be fixed by the manufacturer. The third stage is then the Inspection and Maintenance (I/M) programmes run by several states (He & Jin, 2017).

In Europe, the basic TA stage has been the only legal obligation, and no ISC has been required, with the exception of Sweden that had nationally a U.S.-like in-service conformity programme before they joined the EU, and were allowed to continue with it. Now ISC is also mandatory in EU, with the adoption of new regulations for ISC and Real Driving Emissions (RDE) along with the new WLTP (World-Harmonised Light-Vehicle Test Procedure) applicable to Euro 6d cars, implemented progressively from year 2018. (Williams&Minjares, 2016) The latest addition is the "market surveillance" aspect that allows national TA authorities to perform ISC type of testing using the RDE/PEMS setup for any vehicle that is marketed in the country, and not just those that they have originally type approved, as was the case before (Continental, 2019).

In U.S., EPA has also succeeded in setting type approval (TA) limit values that are applicable to much higher mileages, because current Tier 3 limit values for the time period of 2017 to 2024 are up to 150 000 miles (appr. 241 000 km) or 15 years, whereas the current European Euro 6d is valid only up to 100 000 km (or 5 years) for In-service Conformity (ISC). However, the type approval requires a 160 000 test to validate the EAT system durability. Thus, we can argue that the U.S. cars have some advantage over the European ones regarding in-built robustness and durability in normal service conditions. Furthermore, in U.S., the extended warranty that the manufacturers have on the EAT system is also more stringent, requiring the OEMs to repair failing vehicles, should they prematurely fail in emissions testing (Continental, 2019).

However, I/M programmes in U.S. have not shown an overall success in curbing the excess emissions while the vehicles age, especially, if judged by their cost-effectiveness. Nor has EPA been able to set clear limit values or cut-points for I/M tests that are determined as part of the TA process and testing. The same applies largely also to Europe, even if the present PTI testing for CO and HC is using specific limit values that are issued by the car manufacturer, because in real-terms emissions of CO and HC are no more considered as air quality problem, but the real precursors today are NOx and (small) particulates that are not yet addressed by the PTI procedures.

Furthermore, despite plentiful and proficient studies and literature in the subject, the European legislation on the common (minimal) PTI procure regarding exhaust emissions remains highly inadequate to address the needs to evaluate in-use performance of the present-day EAT systems applied in all stages of the type approval legislation regarding the precursors of crucial pollutants (NOx, PN) leading to inadequate local air quality. Also, amendments of PTI procedures are way behind the introduction of EAT in vehicles because of more stringent TA rules. The issue is more of a legislative case, because as previous chapter have shown, several large-scale studies have developed and presented procedures applicable to NOx and PM/PN that could be implemented as parts of the PTI regulations, but the EC has failed to do so by today.

2.6 Other types of emissions detection for trapping high emitters

2.6.1 Remote Sensing Technologies

Remote sensing of the concentration of various pollutants in the exhaust plume of a passing vehicle is a technology originally developed in late 1980's in Denver University by Donald H Steadman and his colleagues. It was first presented as CO and CO_2 only version (Bishop et al., 1989), but later a HC channel was also added (Guenther et al., 1995). In the beginning it was seen as a tool to assess the assumptions of emissions factors in fleet emissions models such as MOBILE3 and MOBILE4, developed by U.S.EPA. (Steadman, 1989)

However, as the technology allowed screening of large volumes of vehicle in relatively short time and reasonably costs, it was also more widely employed and used to evaluate the effects of some local programmes like "Colorado Oxygenated Fuel Program" in 1988. (Steadman, 1989)

Furthermore, one of the first findings with this type of fleet-wide measurements was that 10% of the vehicles produce more than 50% of the emissions (then CO). (Steadman 1989) This signalled that some vehicles are – for one reason or another – emitting at higher rates, and detecting as well as rectifying those vehicles would yield to good return in emissions reductions. RSD was used early on also assess the I/M programmes. (Steadman et.al., 1996), (Steadman et.al., 1997), (Steadman et.al., 1998)

The collected datasets from various measurement sites and recurring campaigns have been actively used to follow the evolution of the emissions of the U.S. motor vehicle fleet over several decades, and a vast improvement can be seen. (Bishop&Haugen, 2018) (Bishop, 2019)

Today, a fully functional RSD set-up has in addition to a pollutant analyser (EDAR) a camera device for linking the measured values to a license plate, and in some case even with vehicle make, model etc. data retrieved on-line OTA from a registration database. Furthermore, additional information of the acceleration of the vehicle during exhaust plume scanning is provided. Figures 2-10 and 2-11 portray two different alternatives for setting up the devices.

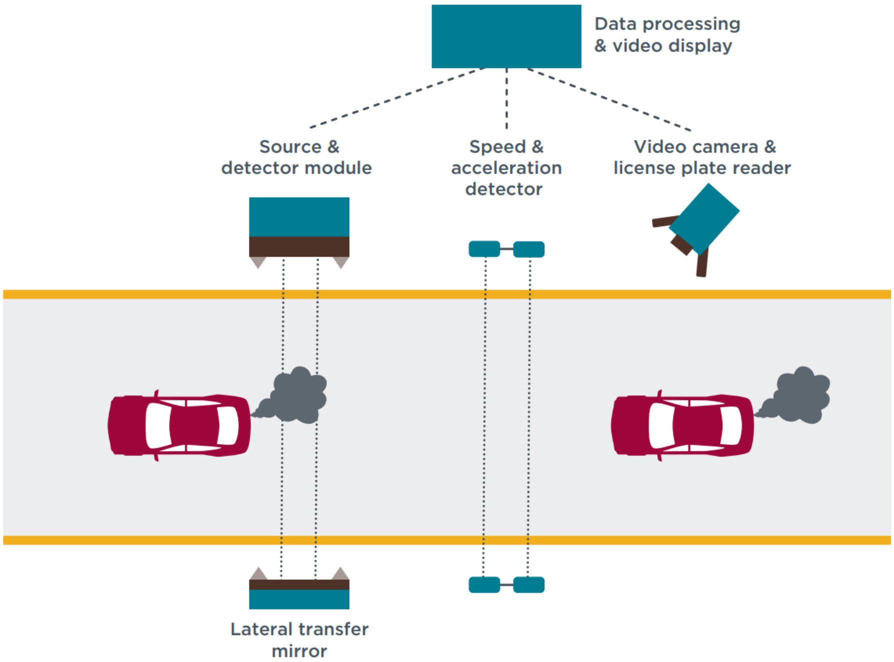


Figure 2-10: Schematic setup of the three units of the remote sensing device *(Source: ICCT 2018)*

Remote sensing technology was commercialised by Envirotest Corp. (USA), and state-of-art systems are now offered by Opus Inspection that amalgamated Envirotest in a merger in 2013. The latest model RSD 5000 adds nitrogen dioxide (NO_2) to pollutants detected by the earlier device's nitrogen monoxide (NO), CO, carbon dioxide (CO_2), hydrocarbons (HC), and opacity. (ICCT, 2019)

Laser-based analysers have been also been used for over 20 years for on-road remote sensing (Nelson et.al., 1998), and a relatively recent incarnation of laser detection technology is called EDAR[1] (Emissions Detection And Reporting), manufactured by Hager Environmental & Atmospheric Technologies (HEAT). It uses a laser light source above street level along with reflective strips on the road surface to enable top-down open path remote sensing of CO, CO_2, NOx, HC and PM. Unlike the more traditional UV and IR-light-based systems, the EDAR system has the capability to scan a two-dimensional image of the exhaust plume. This has the potential to allow for an absolute measurement of each pollutant, as compared with measuring each pollutant as a ratio to CO_2. More details of this system are available in (Ropkins, 2017).

[1] https://www.heatremotesensing.com/edar

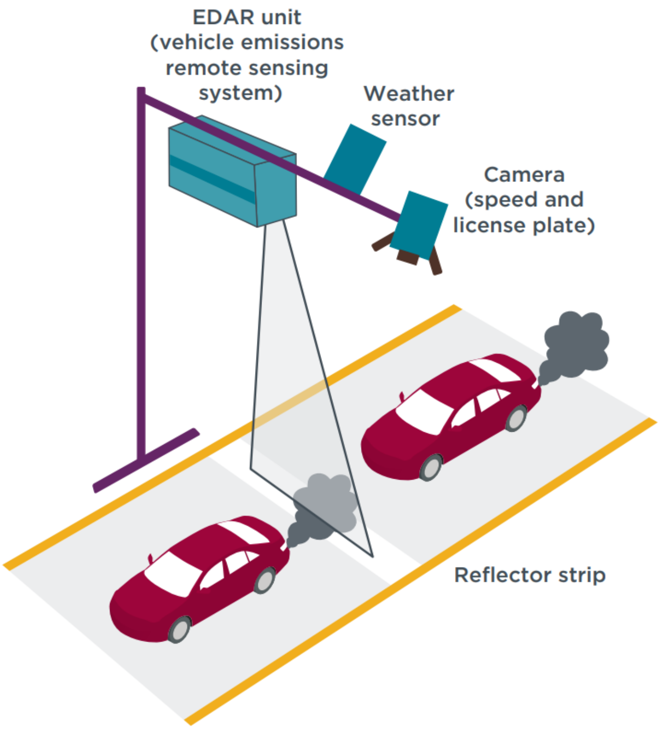


Figure 2-11: Alternate setup for remote sensing devices *(Source: ICCT, 2018)*

By design, both above-mentioned technologies are *open path* technologies. For remotes sensing some *extractive systems* have also been studied. Extractive remote sensing captures a portion of the target vehicle exhaust plume and directs it to analysers to measure pollutant concentrations. Its advantage is that more precision is achieved, but extractive remote sensing systems can measure fewer vehicles in same amount of time than open path systems. (ICCT, 2019)

This capturing of sample can be made from a moving vehicle either by a moving sampler, usually a “chase car” that uses a “scoop” to catch some exhaust from the plume exiting from the tailpipe of the target vehicle. In this technology all analysers must also be in the chase car, which limits their size and technology. This kind of emission measurements has been performed in various different locations, such as in China (Wang et.al., 2012), Finland (Pirjola et.al., 2016), Slovenia (Ježek et.al., 2015) and UK (Ropkins, 2017). The last one is particularly interesting, as it entails a comparison between EDAR and “chase car” type of emissions analysis

However, in a stationary system sampling exhaust either from above of the vehicle or down below it. Here the analysers can be more traditional and more powerful. An example of a study using this kind of sensing is (Peitzmeier et al., 2017).

Table 2-2: Main remote sensing technologies and manufacturers *(Source: ICCT, 2019)*

Type	Position	Provider / Inventor	Equipment name	Measurement	Measures
Open path	Cross-road	University of Denver	FEAT	Arc lamp light beam with mirror reflector	CO, HC, CO_2, NO, NO_2, NH_3, SO_2, opacity
	Cross-road	Opus	RSD 4600 and older	Arc lamp light beam with mirror reflector	CO, HC, CO_2, NO, opacity
			RSD 5000		CO, HC, CO_2, NO, NO_2, NH_3, opacity
	Cross-road	Environmental Technology Consultants	R-series S650	Arc lamp light beam with mirror reflector	CO, CO_2, HC, NO, NO_2
	Cross-road; Overhead	Dopler Eco Technologies	DPL7000 Series	Laser light beam with mirror reflector	CO, CO_2, HC, NO, opacity
	Overhead	HEAT LLC	EDAR	Laser curtain with strip reflector	CO, total and speciated HC, CO_2, NO, NO_2, opacity
	Overhead	Anhui Baolong		Arc lamp light beam with mirror reflector	CO, CO_2, HC, NO, opacity
Extractive	Overhead sampling	University of California, Berkeley		Exhaust plume sample	CH_4, NO, NO_2, NH_3 BC, PM, PN, PN size,
	Overhead sampling	CARB	Portable Emissions Acquisition System (PEAQS)	Exhaust plume sample	Black carbon and NO_x
	Overhead sampling in Shed	University of Denver	OHMS	Exhaust plume sample	CO, CO_2, HC, NO, NO_2, N_2O, PM, PN, Black Carbon
	Roadside sampling	Czech Technical University		Exhaust plume sample	CO, CO_2, NO_x, PM, PN
	Roadside sampling	University of Münster		Exhaust plume sample	NO_x, CO_2, PN
	Plume chaser	University of Heidelberg	ICAD	Exhaust plume sample	NO, NO_2, CO_2
	Plume chaser	University of Birmingham	SNIFFER	Exhaust plume sample	NO, NO_2, CO_2
	Plume chaser	CARB	Mobile Measurement Platform (MMP)	Exhaust plume sample	CO, CO_2, HC, NO_x, PM, PN, Black Carbon

2.6.2 Application campaigns

Use of remote sensing for emissions measurements has not been particularly blooming in Europe, but some efforts were started as early as 1990s for research purposes in Sweden (Sjödin, 1994) and UK. However, during the past decade there has been a proliferation of efforts. The vast majority of projects employed crossroad open path systems, although recent projects in England, Scotland and France used the overhead configuration. (ICCT, 2019)

In 2016, the Bundesamt für Umwelt (Switzerland's Federal Office for the Environment) funded the CONOX project to compile remote sensing findings from Switzerland, Sweden, the United Kingdom, France, and Spain since 2011 to build a European remote sensing database. In 2018, multiple reports were published leveraging the more than 700,000 measurements from the CONOX database (Chen & Borken-Kleefeld, 2014), (Borken-Kleefeld et al.,2018a), (Sjödin et al., 2018), (Jens Borken-Kleefeld et al., 2018b)

The Real Urban Emissions initiative (TRUE) and others have continued to build up the database with hundreds of thousands of new records being taken in 2018 alone, including more than 100,000 in London (Dallmann 2018) and more than 200,000 in Paris (Dallmann 2019).

2.6.3 Use of RSD data

Remote sensing measures an instantaneous emission rate of individual vehicles as they pass by the instrument location. It is not an exact measurement, but the results are rather expressed as emissions in g per g of fuel burned. Furthermore, location of the measurement site and ambient conditions influence the results, and the reliability of the results depends to a large extent on the overall sample size. Moreover, increasing the number of sites increase the representativeness of the measurements for a wider area.

Anyhow, RSD data is not particularly good for assessing emissions of individual vehicles, but rather giving the characteristics of fleets. For these reasons, the questions that RSD can answer are according to (ICCT 2018) the following:

1. Air quality monitoring, planning, and vehicle emission models: What is the average emission rate for the fleet, for different vehicle types, by emission standard, under real-driving conditions, and at different traffic locations, as well as their development over time?

2. In-use surveillance: What is the average emission rate by manufacturer and by model under real-driving conditions for statistically representative samples? What is the long-term durability of exhaust after-treatment systems?

3. Vehicle inspection and maintenance: Does an individual vehicle have suspiciously high pollutant emissions in real driving? Or, inversely, is this vehicle's after-treatment well maintained and can it be exempted from vehicle inspection?

An example of using RSD data to characterise the fleet in some locations is given in Fig. 2-12.

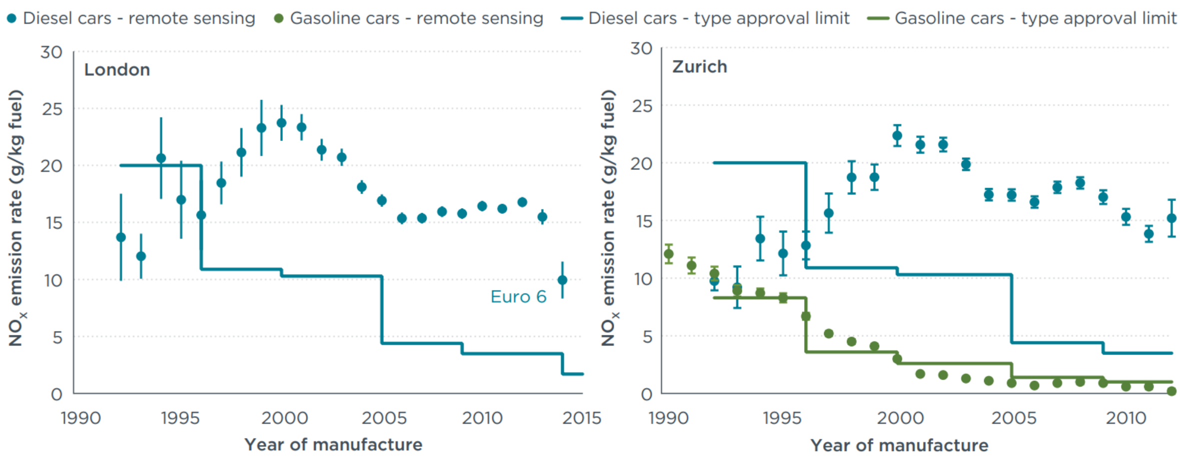


Figure 2-12: NOx emission rates of diesel cars by year of manufacture from remote sensing campaigns in (left) London 2012 and 2013, and (right) Zurich, 2000—2012 *(Source: ICCT, 2018)*

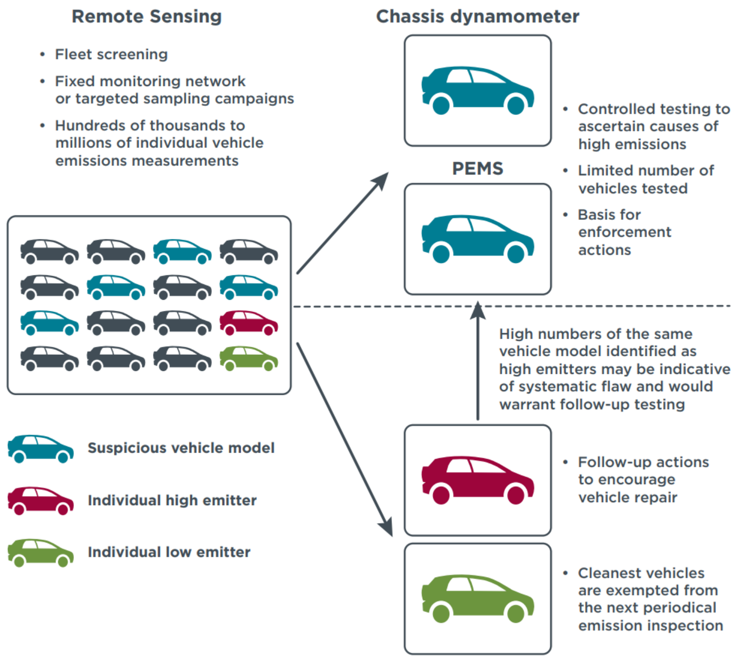


Figure 2-13: Possible applications of vehicle remote sensing in an enhanced vehicle emissions control program *(Source: ICCT, 2019)*

3 Review of the on-board diagnostics protocols

In the 1980s the California Air Resources Board (CARB) realised that the emission of cars and trucks must be ensured not only at the time of registration of the vehicle but also during its entire lifecycle (CARB, 2020; Alvear et.al., 2014). Therefore, it was decided that each vehicle starting in 1988 must have their own electronic system to perform self-monitoring and self-diagnostic in regard to emission relevant values. Each identified error must be signalled by a *Malfunction Indicator Light (MIL)* and additionally stored inside a readable internal memory. This regulation on *On-Board-Diagnostics (OBD)*, as described in section 3.1, demanded that only a few relevant values must be able to be monitored. But the regulation failed to provide a global standardisation framework that each manufacturer had to follow. As a consequence, different types of connectors where used and vendor-specific tools had to be used to scan the system state of their brand. Additionally, this first OBD-I standard failed to identify or progressively monitor certain problems like broken or missing catalytic converters, or the deterioration of critical components that are relevant in regard to emissions.

As a consequence, the new OBD-II standard was developed to take all seven layers of the OSI model into consideration. It covered the lower layers with the standardisation of the 16-pin *Data Link Connector (DLC)* and its pinout and the higher layers with the definition of identifiers of *Electronic Control Units (ECUs), Service- and Parameter IDs (SID/PID)* to request and provide information and most important with the standardisation of *Diagnostic Trouble Codes (DTC)*. The standard is flexible enough so that vendors are able to use their own DTCs for car-specific properties, without interfering with the standardised codes. This new OBD-II standard was introduced in the USA around 1994 and is mandatory in the EU for all petrol engines sold since 2001 and for all diesel engines since 2004. The European regulation of OBD-II is often referred as EOBD, but the regulation itself does not use that abbreviation.

3.1 Interconnected systems inside vehicles

A vehicle consists of many electronic systems and sub-systems that are controlled by *Electronic Control Units (ECUs)*. ECUs are a set of modules (micro-controllers) that represent the core of the electronic embedded system in the vehicle, as they ensure the control and monitoring functions of the engine. The built-in ECUs can be reprogrammed, and their features can be fine-tuned to allow engine functions modification at various performance and economy levels. Examples for such ECUs are engine control units, the braking system, but also climate control or the navigation system. The figure in the next chapter gives some examples of ECUs and how they are divided into sub-networks.

Since the problem of interconnecting control units and systems is not limited to vehicles only, several bus systems have been developed over time, but some with the automotive use in mind. The most prominent one is the two-wire *Controller Area Network (CAN)* bus. It has to be used in modern vehicles to fulfil legal requirements, which are mainly to allow car diagnostics without having to know manufacturer-specific details. This bus can be used to exchange short messages between every device at a maximum rate of 1 MB/sec.

On top of the CAN bus are implemented a set of higher-layer protocols, the most popular of which are:

- For **personal cars**, the minimal sets of functionalities are defined in the *OBD* standard, which is extended by the *Unified Diagnostic Service (UDS)* standard. *OBD* is an embedded system which was introduced in the car market starting from 1987 after the application of the *Clear Air Act*

Amendment, for vehicles and trucks with the aim of monitoring the performance of engine components. It has the ability of registering and reporting issues that might be occurring in a vehicle, such as low performance, low fuel economy, or heavy emissions. A second version (OBD-2, OBD-II or EOBD in Europe) was introduced in 1996. Many available information can be retrieved via OBD such as: oil temperature, speed, engine RPM, pedal position, airflow rate, coolant liquid temperature, or emission status. Identifying anomalous behaviours can be done by reading the *DTCs* that are stored in the memory, hence allowing to more specifically determining the main problem of the vehicle. In the rest of the document, to avoid confusion, we will simply use the keyword "OBD" to refer to the latest available version.

- Beside cars, **utility vehicles**, **heavy-duty vehicles**, or **commercial vehicles** make heavy use of the CAN bus, but by the use of other higher-layer protocols such as the *SAE J1939* standard, which fulfils similar purposes than the OBD/UDS standards but with specific functionalities for heavy-duty vehicles.

This chapter details these protocols, using the *Open Systems Interconnection (OSI)* model as a reference to describe their role in relation to the main vehicle categories covered by the project. It stars with a description of the lower OSI layers that are relevant in the context of diagnostics, before climbing up to higher OSI layers. Table 3-2 below gives an overview of the existing standards by vehicle type to guide the reader through the document. References are only given in case information was not taken directly from the standards.

3.2 Overview of bus systems in automotive

Several bus systems fulfil different requirements and a separation of these purposes makes perfect sense to increase the stability of the overall architecture. As an example, the streaming of audio and video on the same bus that also transports system critical information (use of brakes, crash information) would increase the risk of lost or delayed information and so increases the risk of unnecessary ore more heavy accidents. Additionally, if the amount of some type of data that is created inside cars, e.g. video streams, exceeds the limits of conventional bus systems, then they will require an alternative bus with different properties in regard to throughput and latency.

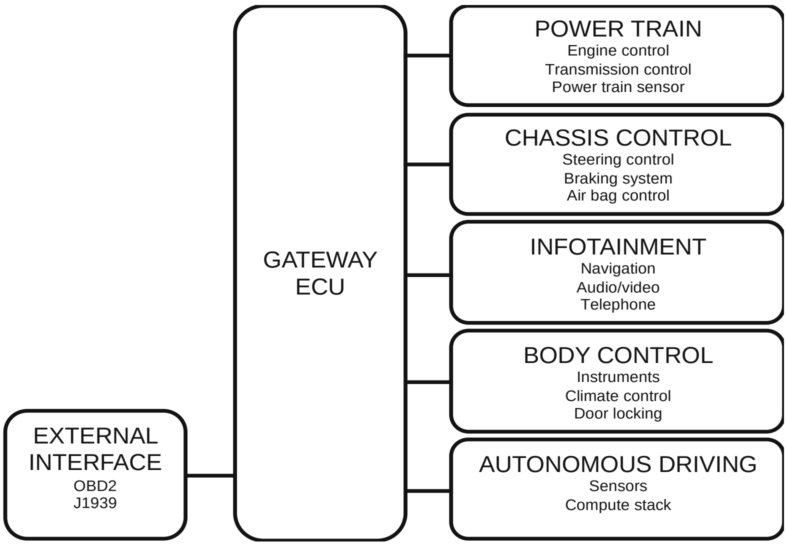


Figure 3-1: Car Electronic Control Units and sub-networks

For all these reasons, the overall network is divided into sub-networks, which might rely on different bus standards. As described in the figure above, a commonly accepted separation is composed of five sub-networks: *Power Train*, *Chassis Control*, *Infotainment*, *Body Control*, and *Autonomous Driving*. Each sub-network uses the bus system that fulfils best its needs. In the centre of all these sub-networks, an ECU gateway allows communication between sub-networks based on different standards.

The table below shows some examples of bus systems and their standards that are used or have been used in vehicles. In relation to diagnostics, only the CAN bus is relevant today.

Table 3-1: Bus systems in automotive applications

Bus	Standard	Description
CAN	ISO 11898 SAE J2284	Controller Area Network Serial bus with high- and low-speed option with event based random bus access Allow communication between ECUs and sensors with prioritized message Random bus access
K-Line	ISO 9141 ISO 14230	Bidirectional solid-core solution to access ECUs Connections between sender and receiver have to be established and closed Mainly obsolete and replaced by CAN in new projects
J1850	SAE J1850	Serial bus Standardized access to vehicular network for onboard diagnostics Mainly obsolete and replaced by CAN in new projects
Ethernet	IEEE 802.3	Mainly for data intensive purposes Used mostly for UDP only, without TLS
LIN	ISO 17987	Local Interconnected Network Serial bus with time-based controlled bus access (delegated token) Integration of sensors and actors
FlexRay	ISO 17458	Serial, deterministic and fault-tolerant bus for system-critical applications Allows both synchronous (real-time) and asynchronous data transfer
MOST	ISO 21806	Media Oriented System Transport Synchronous ring bus system to transmit audio, video, voice and data via plastic optical fibre

Table 3-2: Overview of the existing standards by vehicle type (numbers of standards only)

OSI Layer			CAN			Passenger Cars: UDS	Passenger Cars: OBD	Passenger Cars: WWH-OBD	Trucks and Bus: J1939	Trucks and Bus: J1939	Tractor with Trailers	Tractor with Trailers
7	Application Layer					ISO 14229-1 ISO 14229-3	ISO 15031-5 / SAE J1979	ISO 27145-3	SAE J1939-71 SAE J1939-73	SAE J1939-01 SAE J1939-81	ISO 11992-4	ISO 11992-2 ISO 11992-3
6	Presentation Layer						ISO 15031-2 / SAE J1930-DA ISO 15031-5 / SAE J1979-DA ISO 15031-6 / SAE J2012-DA	ISO 27145-2 / SAE J2012-DA	SAE J1939-DA (SPN) SAE J1939 Appendix C (SPN) SAE J1939-73 Appendix A (FMI)			
5	Session Layer					ISO 14229-2					ISO 14229-2	
4	Transport Layer					ISO 15765-2		ISO 27145-4			ISO 15765-2	
3	Network Layer								SAE J1939-31			
2	Datalink Layer	LCC - Logical Link Control	CAN Controller	ISO 11898-1		ISO 15765-4			SAE J1939-21		ISO 11898-1	
		MAC - Medium Access Control										
1	Physical Layer	PLS - Physical Media Signalling							SAE J1939-11 SAE J1939-12 SAE J1939-14 SAE J1939-15		ISO 11992-1	
		PMA - Physical Medium Attachment	CAN Transceiver	ISO 11898-2 ISO 11898-3 ISO 11898-4 ISO 11898-5 ISO 11898-6	SAE J2284-1 SAE J2284-2 SAE J2284-3 SAE J2284-4 SAE J2284-4							
		PMS - Physical Medium Specification	CAN BUS Medium									
		MDI - Medium Dependent Interface	CAN Bus Connector									

Table 3-3: Overview of the existing standards by vehicle type (numbers of standards only)

	Passenger Cars			Trucks and Bus	Tractor with Trailers
CAN	UDS	OBD	WWH-OBD	J1939	
ISO 11898-x Road vehicles - Controller area network (EU Standard)	**ISO 15765-x Road vehicles — Diagnostic communication over Controller Area Network (DoCAN)**		**ISO 27145-x Road vehicles — Implementation of World-Wide Harmonized On-Board Diagnostics (WWH-OBD) communication requirements**	**SAE J1939-xx Recommended Practice for a Serial Control and Communications Vehicle Network** (US Standard - Truck and Bus)	**ISO 11192-x Road vehicles — Interchange of digital information on electrical connections between towing and towed vehicles**
SAE J2284-x High Speed CAN for Vehicle Applications (US Standard - Passenger Cars)	**ISO 14229-x Road vehicles — Unified diagnostic services (UDS)**	**ISO 15031-x Road vehicles — Communication between vehicle and external equipment for emissions-related diagnostics**			

3.3 CAN bus

The CAN bus is a serial bus system that was developed in the 1980s by Bosch and Intel to reduce the overall length of the installed wires inside a vehicle.

3.3.1 Standards overview

Table 3-4: Standards of the CAN Bus relation to OSI layers

<table>
<tr><th colspan="3">OSI Layer</th><th colspan="3">CAN</th></tr>
<tr><td>7</td><td colspan="2">Application Layer</td><td colspan="3" rowspan="5"></td></tr>
<tr><td>6</td><td colspan="2">Presentation Layer</td></tr>
<tr><td>5</td><td colspan="2">Session Layer</td></tr>
<tr><td>4</td><td colspan="2">Transport Layer</td></tr>
<tr><td>3</td><td colspan="2">Network Layer</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">Datalink Layer</td><td>LCC - Logical Link Control</td><td rowspan="3">CAN Controller</td><td colspan="2" rowspan="3">ISO 11898-1</td></tr>
<tr><td>MAC - Medium Access Control</td></tr>
<tr><td rowspan="4">1</td><td rowspan="4">Physical Layer</td><td>PLS - Physical Media Signalling</td></tr>
<tr><td>PMA - Physical Medium Attachment</td><td>CAN Transceiver</td><td rowspan="2">ISO 11898-2
ISO 11898-3
ISO 11898-4
ISO 11898-5
ISO 11898-6</td><td rowspan="2">SAE J2284-1
SAE J2284-2
SAE J2284-3
SAE J2284-4
SAE J2284-4</td></tr>
<tr><td>PMS - Physical Medium Specification</td><td>CAN BUS Medium</td></tr>
<tr><td>MDI - Medium Dependent Interface</td><td>CAN Bus Connector</td><td colspan="2"></td></tr>
</table>

The CAN bus is standardised by ISO 11989 and SAE J2284, which describe the two lower layers of the OSI model, i.e. the physical and the data link layers. Excluded from that is the definition of the connector interface (*Medium Dependent Interface - MDI*), as this differs in the OBD and J1939 standards.

Sub-section “

Physical interface” presented below gives an overview of commonly used physical interfaces.

ISO 11989 Part 1 defines the frame structure of the CAN bus. This is important for each protocol that relies on CAN. This frame structure and its use in the various standards are shown in sub-section “CAN messages”.

Parts 2 to 6 of ISO 11898 as well as SAE J2284 are relevant to define different media access speed on the bus. These technical details are not presented in this document.

Table 3-5: ISO 11898: Road vehicles - Controller area network (EU Standard)

ISO 11898 Road vehicles - Controller area network (EU Standard)	
Part 1	Data link layer and physical signalling
Part 2	High-speed medium access unit
Part 3	Low-speed, fault-tolerant, medium dependent interface
Part 4	Time-triggered communication
Part 5	High-speed medium access unit with low-power mode
Part 6	High-speed medium access unit with selective wake-up functionality

Table 3-6: SAE J2284: High Speed CAN for Vehicle Applications (US Standard - Passenger Cars)

SAE J2284 High Speed CAN for Vehicle Applications (US Standard - Passenger Cars)	
Part 1	at 125 kbps
Part 2	at 250 kbps
Part 3	at 500 kbps
Part 4	at 500 kbps with CAN FD Data at 2 Mbps
Part 5	at 500 kbps with CAN FD Data at 5 Mbps

3.3.2 Physical interface

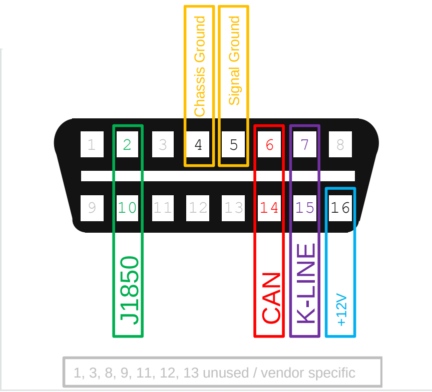
This section shows a number of physical interfaces and the pinouts that make use of the CAN bus (i.e. which pin of the physical interface has which function), as it is used in different standards.

For cars the OBD physical connector is used and demanded by laws and regulations (Figure 3-2). For heavy-duty vehicles, a variant of that connector (OBD Type B /HD OBD) is in use that differs in the two ways. Instead of 12V power as in the OBD connector, the Type B connector uses 24V as power Figure 3-3). To avoid a plugging of an OBD device that only accepts 12V to a Type B interface with 24V, the middle bar has a gap of the male connector and a barrier in the female counterpart. On the other side, it is possible to plug in Type B equipment to an OBD connector of a car.

A third difference is, that even if a variant of the OBD connector is used for heavy-duty vehicles, instead of the OBD protocol, the J1939 protocol is exchanged via the CAN bus. Alternatively, trucks and heavy-duty vehicles might us the 9-pin J1939 connector (Figure 3-4). Adapters exist, that map the OBD connector to the J1939 connector (Figure 3-5).

The CAN bus is not limited to vehicles only and is used, e.g. for automation. CiA (CAN in Automation) has standardised a variety of connectors for CAN, e.g. the 9-PIN D-SUB interface (Figure 3-6) as defined in CiA DS-102, or the RJ45 connector (Figure 3-7) as defined in the CANOpen standard CiA DR-303-1.

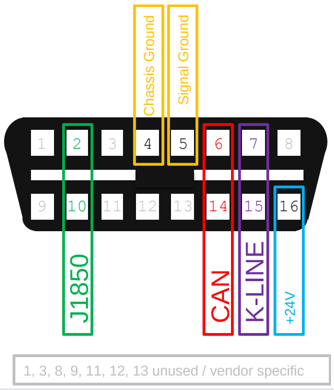
3.3.2.1 *OBD (passenger cars)*



Bus	Pin	Signal	Description
	16	Power	+12V
	4	Ground	Chassis ground
	5		Signal ground
J1850	2	J1850 Bus+	SAE J1850 PWM and VPW
	10	J1850 Bus	SAE J1850 PWM only
CAN	6	CAN High	CAN ISO 11898 and SAE J2284
	14	CAN Low	
K-Line	7	K-LINE	K-Line of ISO 9141-2 and ISO 14230-4
	15	L-LINE	

Figure 3-2: Car OBD II physical connector and pinout

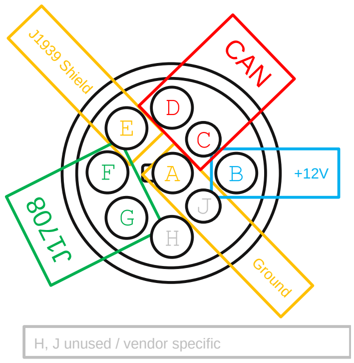
3.3.2.2 OBD Type B/HD OBD (heavy-duty)



Bus	Pin	Signal	Description
	16	Power	+24V
	4	Ground	Chassis ground
	5		Signal ground
J1850	2	J1850 Bus+	SAE J1850 PWM and VPW
	10	J1850 Bus	SAE J1850 PWM only
CAN	6	CAN High	CAN ISO 11898 and SAE J2284
	14	CAN Low	
K-Line	7	K-LINE	K-Line of ISO 9141-2 and ISO 14230-4
	15	L-LINE	

Figure 3-3: OBD II Type B physical connector and pinout with 24V and gap in the middle bar

3.3.2.3 J1939 (utility vehicle, heavy-duty vehicle, commercial vehicle)



Bus	Pin	Signal	Description
	B	Power	+12V
	A	Ground	Ground
	E		J1939 Shield
J1708	F	J1708/J1587 High	SAE J1850 PWM and VPW
	G	J1708/J1587 Low	SAE J1850 PWM only
CAN	C	CAN High	CAN ISO 11898 and SAE J2284
	D	CAN Low	CAN ISO 11898 and SAE J2284

Figure 3-4: J1939 physical connector and pinout

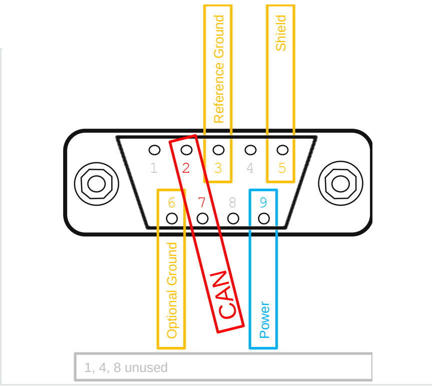
3.3.2.4 J1939 to OBD adapter

J1939	
Pin	**Signal**
B	+12V Power
A	Ground
E	J1939 Shield
F	J1708/J1587 High
G	J1708/J1587 Low
C	CAN High
D	CAN Low

OBD	
Pin	**Signal**
16	+12V Power
4	Chassis ground
5	Signal ground
2	J1850 Bus+
10	J1850 Bus
6	CAN High
14	CAN Low
7	K-LINE
15	L-LINE

Figure 3-5: J1939 to OBD pinout mapping

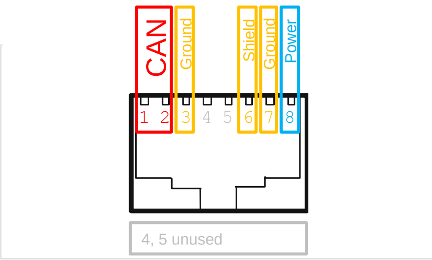
3.3.2.5 CiA - CAN in Automation (CiA DS-102: D-SUB 9-Pin)



Bus	Pin	Signal	Description
	9	Power	Optional, if bus power or external VBAT is required
	3	Ground	CAN reference ground
	5		Optional CAN shield
	6		Optional CAN reference ground
CAN	7	CAN High	CAN ISO 11898 and SAE J2284
	2	CAN Low	

Figure 3-6: CiA DS-102 D-SUB 9-Pin physical connector and pinout

3.3.2.6 CANOpen (CiA-DR-303-1: RJ45)



Bus	Pin	Signal	Description
	8	Power	+24V Optional external
	3	Ground	CAN ground
	6		Optional shield
	7		CAN ground
CAN	1	CAN High	CAN ISO 11898 and SAE J2284
	2	CAN Low	

Figure 3-7: CANOpen CiA-DR-303-1 RJ45 physical connector and pinout

3.3.3 CAN messages

A CAN message or CAN frame is specified in ISO 11898 Part 1. It exists in four different versions (Cook et.al., 2019; CSS Electronic, 2020a):

- *Data frame:* Provides data from an ECU to a testing device or other ECU
- *Remote frame:* Requests data from an ECU
- *Error frame:* Indicates errors on the bus
- *Overload frame:* Indicates, that the processing by an ECU of a request requires more time.

In the following only data and remote frames are explained.

3.3.4 Message structure

The CAN standard makes a difference between *Logical Link Control* (*LCC)* frames and *Medium Access Control* (*MAC)* frames*,* which are defined in the two sub layers of the OSI data link layer. An LCC frame consists of an *Identifier field*, a *Data length code field* and a *Data field*. The data field only exists in the data frame, but not in the remote frame.

The identifier field contains the 11-bit *Base Identifier* (CAN 2.0A message; CAN 2.0B standard message) and optionally an additional 18-bit *Extended Identifier* (CAN 2.0B extended message). The identifier therefore can be 11 or 29 bits long.

The *Data length code field* simply describes how many bytes of data will follow in the *Data field*.

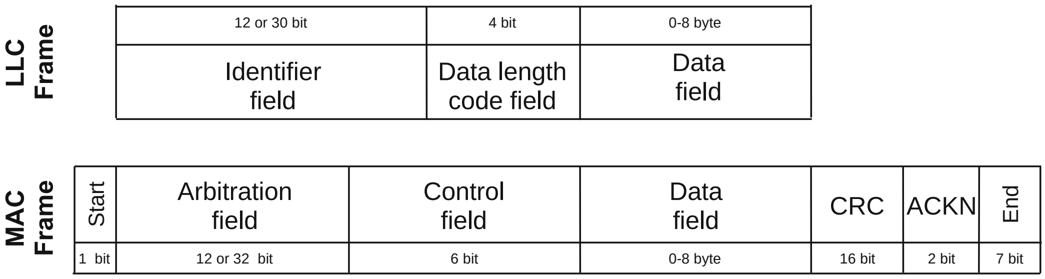


Figure 3-8: LCC Frame and MAC Frame pinout

The information of the LCC Frame are encapsulated inside a MAC frame, but the information of the identifier field and the data length code field are integrated inside an *Arbitration field* and a *Control field*. Additional bits indicate the start and end of the frame, allow to perform integrity checks and support to acknowledge the receiving of a message. In the following the structure of the MAC frame is synonymous for the *CAN Message*.

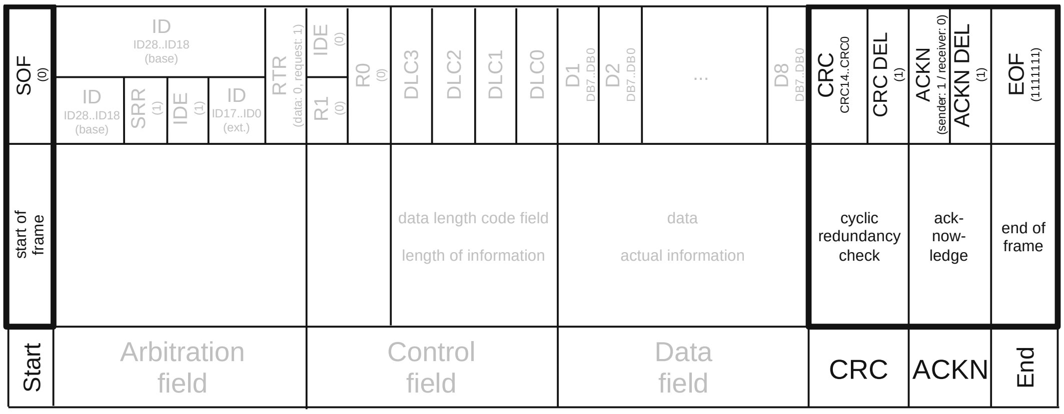


Figure 3-9: Start, end, redundancy check and acknowledge

All CAN messages start with one bit *Start of Frame (SOF),* and end with seven bits *End of Frame (EOF)*. The *Cyclic Redundancy Check (CRC and CRC delimiter)* follows right after the data field and is followed by an *Acknowledge (ACKN and ACKN delimiter)* to identify that the message was received.

The CRC-15 calculation is based on the generator polynomial $x^{15}+x^{14}+x^{10}+x^{8}+x^{7}+x^{4}+x^{3}+1$, which is usually able to detect five-bit errors or burst errors up to 15 bits. Due to the introduction of stuffed-bits (see explanation below), this number is reduced in worst case to the detection of one-bit error only.

A sender / transmitter of a message is able to identify that the message was fully received by a receiver on base of the ACKN bit. The transmitter sends a recessive 1 as ACKN. In case a receiver has fully read the message from the bus and the CRC check was successful, it will put a dominant 0 as the ACKN on the bus, which overrules the 1 from the transmitter. The transmitter will observe the dominant 0 on the bus and can conclude, that at least one receiver has fully accepted the message. In case no one has fully received or accepted the message, the ACKN stays as 1 indicating to the transmitter, that an ACKN error has occurred.

The transmitter will insert *Stuffed Bits* starting at the transmission of the SOF bit until the end of the CRC-check. In case five identical bits have been send, a stuffed bit of the opposite value will be included. In case of five 0, the stuffed bit will be a 1, and in case of five 1, the stuffed bit will be a 0. The reader will identify an error in case six or more bits of the same value have been sent (exception: EOF with 7 time "1"). Each stuffed bit can be transparently removed from the bit-stream.

3.3.5 Standard and extended identifier

In CAN 2.0B, two types of messages are defined, *Standard messages* with an 11-bit identifier, and *Extended messages* with a 29-bit identifier.

The standard message with an 11-bit identifier is structured as follows:

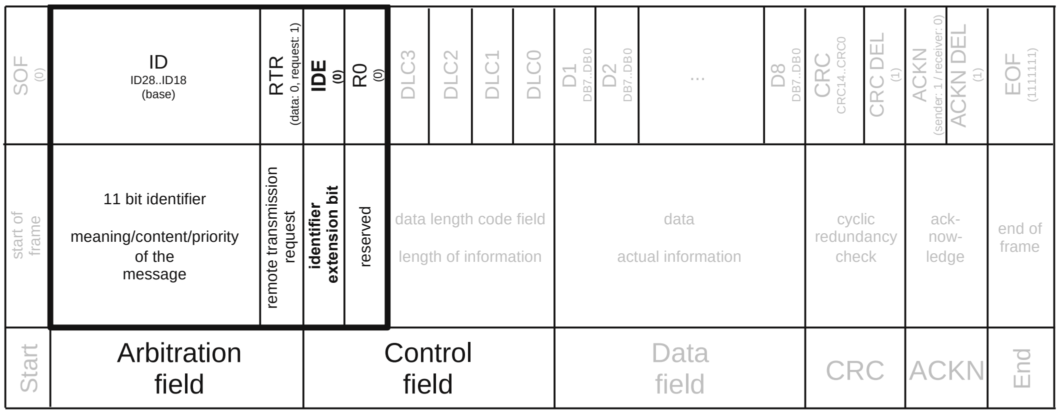


Figure 3-10: Standard message with 11-bit identifier (CAN 2.0B)

The *Identifier Extension Bit (IDE)* is set to 0 showing, that only 11-bit identifier are used. This structure is identical to CAN 2.0A messages, except that they use a reserved R1 bit instead of the IDE bit. Since both bits are 0, there is no real difference to a CAN 2.0A message.

The *Remote Transmission Request (RTR)* bit tells if this frame is a data frame (=0) that contains data, or a remote frame (=1) that requests data. In case that bit is 1, no data field is given.

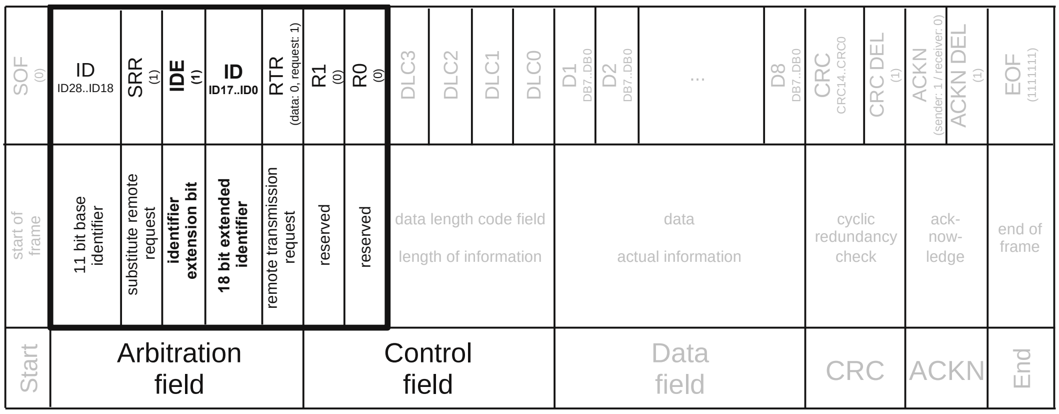


Figure 3-11: Standard message with 11-bit identifier (CAN 2.0B)

The IDE bit is set to 1, indicating a 29-bit identifier. These additional 18 bits follow the IDE bit. The remote transmission request bit RTE that tells if this frame is a data frame or remote frame is moved from the position behind the base 11-bit identifier to the position right after the additional 18 bits of the extended identifier, making it again the next bit after the identifier is fully transmitted. Its original position is replaced by a *Substitute Remote Request* (*SRR) bit* that is only introduces to ensure that the IDE bit is in both cases the 14th bit of the frame. Two reserved bits are introduced right after the RTR bit, ensuring that the data length code is still separated from the RTR bit by two bits.

3.3.6 Meaning and priority of the identifier

It is important to notice that the *Identifier* in CAN does not represent an address but defines the meaning or content of the data that is requested or provided. Parts of the identifier might be understood as address information in the higher OSI layers that make use of the CAN-bus. As an example, the J1939 defines parts of the identifier as from- or to-address.

The identifier is either given as ID28..ID18 or ID28..ID0 so the higher bits of the identifier are transmitted first. In case two sender start to send a frame at the same time, starting with the SOF bit, a dominant 0 will always win on the bus against a recessive 1. A sender who uses a lower identifier and who observes the bus will notice at one moment, that it had sent a 1 but observes a 0 on the bus. In that case, the loosing sender will stop to transmit its frame immediately and try later. The winning sender will not realise that this event has happened and simply continues to transmit. This behaviour creates a priority of identifiers. The lower the value of the identifier is, the higher is its priority.

3.3.7 Data length code field and Data field

The four bits of the *Data length code* describe how many bytes of data will follow in the *Data Field*. Only 0 to 8 bytes are possible, so only combinations from 0000 up to 1000 are valid as a data length code. In case of a remote frame (RTR=0), the data length code is 0, and the data field is skipped.

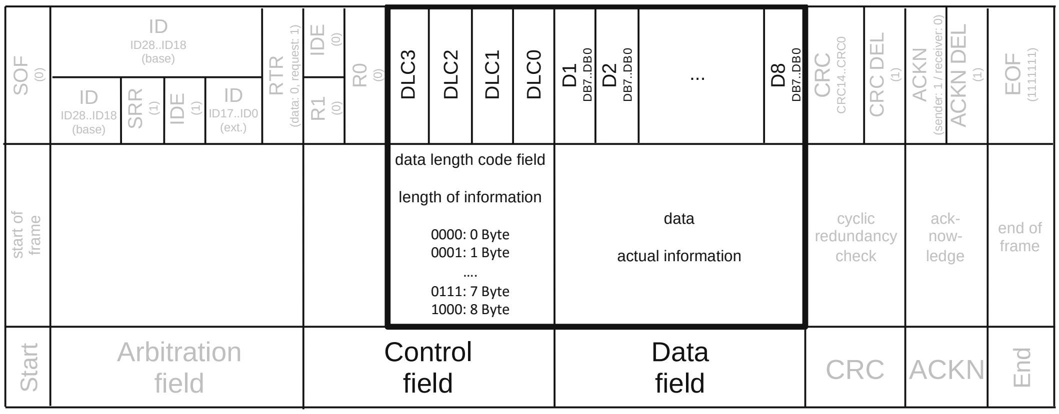


Figure 3-12: Data length code and data

3.3.8 CAN FD

CAN Flexible Data (FD) is the latest extension of the CAN standard and introduces the possibility to transmit up to 64 Bytes of data in a single frame (CAN Newsletter, 2015; CSS Electronic, 2020d). To ensure, that such a CAN FD frame does not block the bus for too long time, a change of transmission speed to a higher speed is possible during the frame transmission.

A CAN FD frame is signalled by the *Flexible Data Rate Format (FDF)* bit, which follows either the IDE bit of the standard message, or the RTR bit of the extended message. In both cases, CAN FD frames do not exist as remote frames, so the remote transmission request has always to be set to 0. To indicate that change of behaviour, the remote transmission request bit is renamed to *Remote Request Substitution (RRS).*

Another *reserved* bit *res* follows which can be used to extend the standard in future. Depending on the number of data bytes a change of speed not always makes sense. Therefore, the *Bit Rate Switch*

(BRS) has to be set to 1 to indicate that a change of speed to a higher speed will immediately follow that bit. The speed it set back to normal speed after the CRC checks are completed.

The *Error State Indicator (ESI)* shows if a node is error active or error passive.

The *Data Length Code Field* is extended with additional combinations, which allow to indicate the transmission of 12, 16, 16, 20, 24, 32, 48 or 64 Byte.

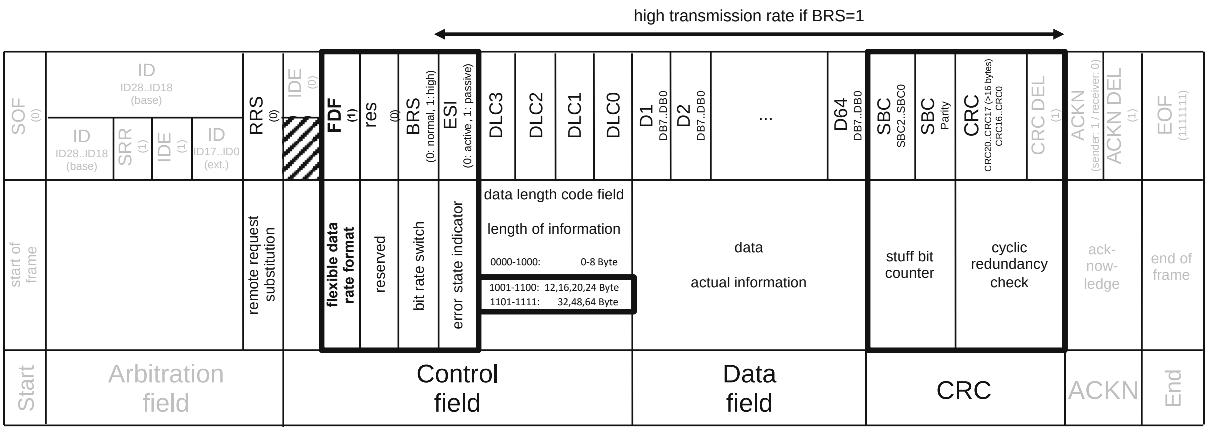


Figure 3-13: CAN FD Message

The CRC section has changed in several ways. First, a three-bit *Stuff Bit Counter (SBC)* is introduced. The gray-encoded value shows, how many stuff-bits modulo 8 have been used in the frame so far. This value is followed by a parity bit of the stuff bit counter. In case that value does not match what is observed or the parity is wrong, an error will be identified.

Depending on the number of bytes that are send in the data field, the CRC values has either 21 bits (CRC-21) or 17 bits (CRC-17). CRC-21 is used for more than16 bytes of data and uses the generator polynomial $x^{21}+x^{20}+x^{13}+x^{11}+x^{7}+x^{4}+x^{3}+1$. CRC-17 is used for less or equal than 16 bytes of data and uses the generator polynomial $x^{17}+x^{16}+x^{14}+x^{13}+x^{11}+x^{6}+x^{4}+x^{3}+x^{1}+1$.

The behaviour to introduce stuff-bits has changed slightly in the CAN FD standard. In the classic CAN standard, stuffed bits are only inserted dynamically in case of need. In CAN HD, the dynamic behaviour changes right after the transmission of the data field to a to a fixed behaviour with stuff bits added at fixed positions.

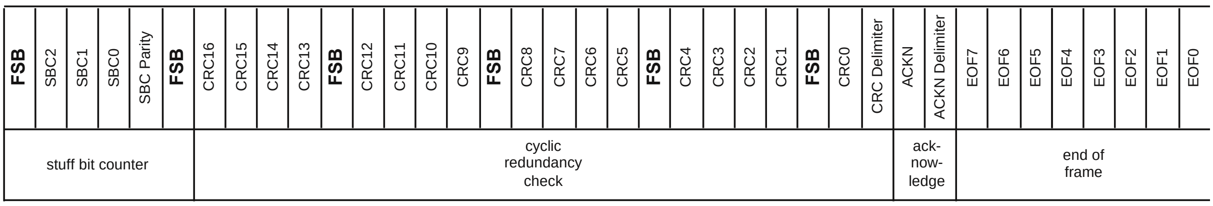


Figure 3-14: Fixed Stuffed Bits in an example with CRC-17

Starting right with a *Fixed Stuff Bit (FSB)* in front of the first bit of the stuff bit counter, every fourth bits is followed by a fifth FSB bit. This behaviour is continued until the acknowledge slot is reached. Each stuff bit has the opposite value of the previous bit.

3.4 Passenger cars: On-board Diagnostics (OBD) and Unified Diagnostic Service (UDS)

Over the years, legal requirements have imposed the use of specific standards in all new passenger cars sold. These standards primarily specify which physical interface is to be provided in the vicinity of the steering wheel and which diagnostic standards are to be provided through that interface. Two standards are important in that context: *On-board Diagnostics (OBD)* and the *Unified Diagnostic Service (UDS)*.

3.4.1 Standards overview

Table 3-7 presents standards of Passenger cars in relation to OSI layers.

Table 3-7: Standards of Passenger Cars in relation to OSI layers

<table>
<tr><th colspan="3" rowspan="2">OSI Layer</th><th colspan="3">Passenger Cars</th></tr>
<tr><th>UDS</th><th>OBD</th><th>WWH-OBD</th></tr>
<tr><td>7</td><td colspan="2">Application Layer</td><td rowspan="2">ISO 14229-1
ISO 14229-3</td><td>ISO 15031-5 / SAE J1979</td><td>ISO 27145-3</td></tr>
<tr><td>6</td><td colspan="2">Presentation Layer</td><td>ISO 15031-2 / SAE J1930-DA
ISO 15031-5 / SAE J1979-DA
ISO 15031-6 / SAE J2012-DA</td><td>ISO 27145-2 / SAE J2012-DA</td></tr>
<tr><td>5</td><td colspan="2">Session Layer</td><td colspan="3">ISO 14229-2</td></tr>
<tr><td>4</td><td colspan="2">Transport Layer</td><td colspan="2" rowspan="2">ISO 15765-2</td><td rowspan="8">ISO 27145-4</td></tr>
<tr><td>3</td><td colspan="2">Network Layer</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">Datalink Layer</td><td>LCC - Logical Link Control</td><td colspan="2" rowspan="6">ISO 15765-4</td></tr>
<tr><td>MAC - Medium Access Control</td></tr>
<tr><td rowspan="4">1</td><td rowspan="4">Physical Layer</td><td>PLS - Physical Media Signalling</td></tr>
<tr><td>PMA - Physical Medium Attachment</td></tr>
<tr><td>PMS - Physical Medium Specification</td></tr>
<tr><td>MDI - Medium Dependent Interface</td></tr>
</table>

In the context of OBD via CAN, the ISO Standard 154765 is important. Part 4 of the standard gives details on which 11-bit or 29-bit identifier are used. The standard also describes how requests and responses are encapsulated into the data field of the CAN frame. This is mainly done with the use of a *Service ID (SID)* and *Parameter ID (PID),* which describe the data.

The set of possible SIDs is extended in the UDS standard ISO 14229. WWH-OBD tries to harmonise vendor specific implementations of OBD and UDS mainly bases on both standard and only slightly extends them (Fellmeth et al., 2010; Frank, 2010; Potter, 2012).

Table 3-8: ISO 15765: Road vehicles - Diagnostic communication over Controller Area Network (DoCAN)

ISO 15765 Road vehicles - Diagnostic communication over Controller Area Network (DoCAN)	
Part 1	General information and use case definition
Part 2	Transport protocol and network layer services
Part 3	Implementation of unified diagnostic services (UDS on CAN)
Part 4	Requirements for emissions-related systems
Part 5	Specification for an in-vehicle network connected to the diagnostic link connector

Table 3-9: ISO 15031: Road vehicles - Communication between vehicle and external equipment for emissions-related diagnostics

ISO 15031 Road vehicles - Communication between vehicle and external equipment for emissions-related diagnostics	
Part 1	General information and use case definition
Part 2	Guidance on terms, definitions, abbreviations and acronyms / SAE J1930-DA
Part 3	Diagnostic connector and related electrical circuits: Specification and use / SAE J1962
Part 4	External test equipment
Part 5	Emissions-related diagnostic services / SAE J1979-DA
Part 6	Diagnostic trouble code definitions / SAE J2012-DA
Part 7	Data link security

Table 3-10: ISO 14229: Road vehicles - Unified diagnostic services (UDS)

ISO 14229 Road vehicles - Unified diagnostic services (UDS)	
Part 1	Application layer
Part 2	Session layer services
Part 3	Unified diagnostic services on CAN implementation (UDSonCAN)
Part 4	Unified diagnostic services on FlexRay implementation (UDSonFR)
Part 5	Unified diagnostic services on Internet Protocol implementation (UDSonIP)
Part 6	Unified diagnostic services on K-Line implementation (UDSonK-Line)
Part 7	UDS on local interconnect network (UDSonLIN)
Part 8	UDS on Clock eXtension Peripheral Interface (UDSonCXPI)

Table 3-11: ISO 27145: Road vehicles - Implementation of World-Wide Harmonized On-Board Diagnostics (WWH-OBD) communication requirements

ISO 27145 Road vehicles - Implementation of World-Wide Harmonized On-Board Diagnostics (WWH-OBD) communication requirements	
Part 1	General information and use case definition
Part 2	Common data dictionary
Part 3	Common message dictionary
Part 4	Connection between vehicle and test equipment

3.4.2 OBD CAN identifier

Inside a vehicle, a number of *ECUs* are installed for which every unit fulfils a different purpose. In the OBD the number of ECUs is limited to 8 and ECU #1 should fulfil the task of an engine control module, while #2 should be the transmission control module. The CAN bus specifications does not foresee to store sender or receiver addresses inside a CAN identifier. In OBD this not fully true. First, The CAN OBD identifier is used to distinguish between data requests and data responses, both of which are based on CAN data frames. Data requests are not based on remote CAN frames, which makes the Remote Transmission Request (RTR) bit of the CAN frame obsolete.

The used OBD CAN identifier additionally identifies from which ECU data is requested or which ECU had provided the data. In case data is specifically requested from specific ECUs, it is called a *physical request*. Alternatively, test equipment is capable of using a generic identifier to request information without specifying which ECU should respond. This is called a *functional request*.

As a consequence, from the huge number of possible CAN identifiers, only seventeen 11-bit CAN identifiers and seventeen 29-bit CAN identifiers are standardised.

Table 3-12: 11-bit OBD CAN Identifier

ECU	request from external test equipment to ECU	response from ECU to external test equipment	Type
#1 Engine control module	7 E0	7 E8	physical
#2 Trans-mission control module	7 E1	7 E9	
#3	7 E2	7 EA	
#4	7 E3	7 EB	
#5	7 E4	7 EC	
#6	7 E5	7 ED	
#7	7 E6	7 EE	
#8	7 E7	7 EF	
-	7 DE	-	functional

Table 3-13: 29-bit OBD CAN Identifier

ECU	request from external test equipment to ECU	response from ECU to external test equipment	Type
#xx xx=1..8	18 DA xx F1	18 DA F1 xx	physical
-	18 DB 33 F1	-	functional

3.4.3 OBD message structure

From the complete CAN message, not all bits are relevant for the understanding of an OBD message: the CAN identifier, the data length code, and the data field. All additional bits are usually not provided to the reader of OBD messages. In OBD, the data length code always is set to 8, making the data field always 8 bytes long. In the data field, the first byte describes the number of actually used data bytes, followed by a *Service ID (SID)* that describes the general service that is requested. SIDs are specified from 01 to 0A for requests. The corresponding responses are always +40, so from 41 to 4A.

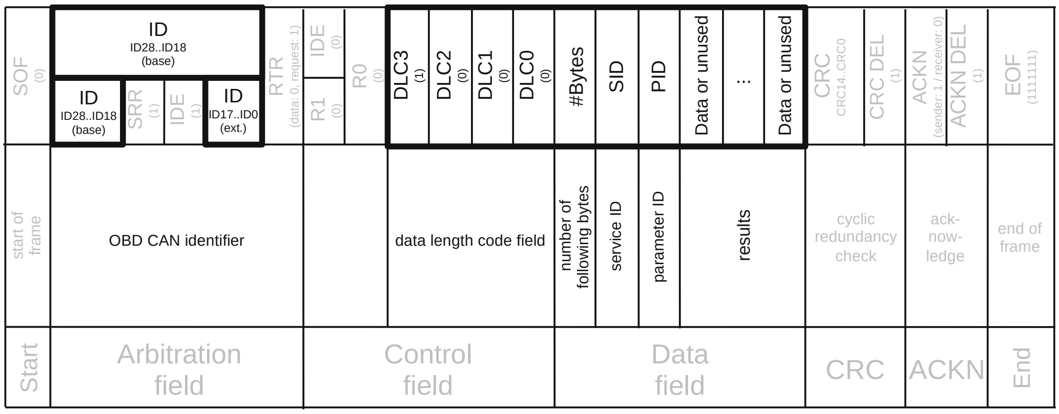


Figure 3-15: OBD message in relation to a CAN message

3.4.4 Parameter and Service ID (PID/SID)

The *Parameter ID (PID)* specifies which set of parameters is requested within the service. Depending on the SID/PID, the following bytes have to be interpreted according to the standard, e.g. by providing a formula plus the unit of the result value. Additionally, the specification tells, which maximum and which minimum is accepted as a valid value.

In case of a request or a response with not all of the eight bytes needed, some additional bytes have to be added to complete the data field. The values of the unused bytes will be ignored.

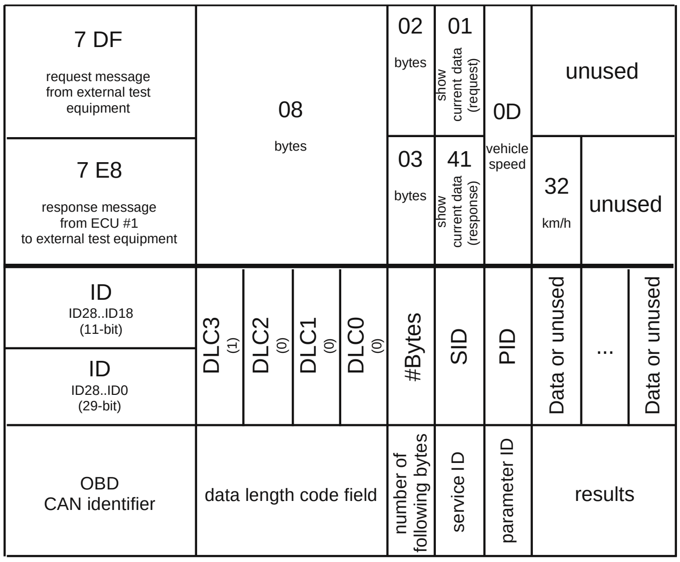


Figure 3-16: Example request and response

In the example below, a test equipment is requesting the current vehicle speed. It uses the identifier 7DF to indicate that the request was send from an external test equipment. Since vehicle speed is linked to engine control, ECU#1 will respond with the identifier 7E8. For both, request and response, the data length code is set to 8. In the data field, the first byte shows for the request that only two bytes are needed to specify the service SID and its parameter PID, while the response is one byte longer, because it includes the value of the speed.

3.4.5 ISO TP

The ISO standard 15765 Part 2 defines how data is transmitted that exceeds the limit of 8 bytes (Strang 2008). In the previous section the #bytes field was defining how may bytes are actually used in the data field. That value is in fact divided into two parts. The first four bits decide if the data is sent as a *Single Frame (SF)* (=0000), as the *First Frame (FF)* of a number of consecutive frames (=0001), or if it is one of the following *Consecutive Frames (CF)* (=0002).

Single frames (SF), use four bits *Data Length (DL)*, which describes how many of the following bytes contain data. In case of a first frame, the data length consists of 12 bytes and so a total of 4096 bytes can be send. The consecutive frame uses four bits as a *Sequence Counter SC*, which counts the number of frames module 16, starting with SC=1.

Single Frame

4 Bit	4 Bit	7 Byte						
0000	DL	Data						
Byte 1		Byte 2	Byte 3	Byte 4	Byte 5	Byte 6	Byte 7	Byte 8

First Frame

4 Bit	12 Bit		6 Byte					
0001	DL		Data					
Byte 1		Byte 2	Byte 3	Byte 4	Byte 5	Byte 6	Byte 7	Byte 8

Consecutive Frame

4 Bit	4 Bit	≤ 7 Byte						
0002	SN	Data						
Byte 1		Byte 2	Byte 3	Byte 4	Byte 5	Byte 6	Byte 7	Byte 8

Figure 3-17: Data extending 8 bytes

Data that is send via multiple frames is responded by the receiver with a *Flow Control FC* (=0003). The *Flow Status (FS)*, tells the sender if it is *Clear To Send (CTS)* (=0), if it should *Wait* (=1) or if the receiver had an *Overflow* (=3). The *Block Size (BS)* tells the sender how many consecutive frames the sender might send in a row before the receiver needs time to process the data. The *Minimum Separation Time* (ST_{Min}) tells the sender, how much time in milliseconds the sender needs to wait between two consecutive frames.

Flow Control

4 Bit	4 Bit	8 Bit	8 Bit
0003	FS	BS	ST_{Min}
Byte 1		Byte 2	Byte 3

Figure 3-18: Flow control

3.4.6 OBD Service IDs

The following table provides the standardised service IDs in OBD when used as a request and when used as a response (Wikipedia, 2020a).

Table 3.14: Services in OBD

Service SID		Description
Request	Response	
01	41	Show current data
02	42	Show freeze frame data
03	43	Show stored Diagnostic Trouble Codes
04	44	Clear Diagnostic Trouble Codes and stored values
05	45	Test results, oxygen sensor monitoring (non CAN only)
06	46	Test results, other component/system monitoring (Test results, oxygen sensor monitoring for CAN only)

Service SID		Description
Request	Response	
07	47	Show pending Diagnostic Trouble Codes (detected during current or last driving cycle)
08	48	Control operation of on-board component/system
09	49	Request vehicle information
0A	4A	Permanent Diagnostic Trouble Codes (DTCs) (Cleared DTCs)

3.4.7 UDS Service IDs

The *Unified Diagnostic Service (UDS)* standard keeps the message and identifier structure from the ISO 15765 standard but provides additional services. The following table provides the standardised additional service IDs in UDS when used as a request and when used as a response (Wikipedia, 2020b).

Table 3.15: UDS Services

Service		Description
Request	**Response**	
10	50	Diagnostic Session Control
11	51	ECU Reset
14	54	Clear Diagnostic Information
19	59	Read DTC Information
22	62	Read Data by Identifier
23	63	Read Memory by Address
24	64	Read Scaling Data by Identifier
27	67	Security Access
28	68	Communication Control
2A	6A	Read Data by Periodic ID
2C	6C	Dynamically Define Data Identifier
2E	6E	Write Data by Identifier
2F	6F	Input Output Control by Identifier
31	71	Routine Control
34	74	Request Download
35	75	Request Upload
36	76	Transfer Data
37	77	Transfer Exit
3D	7D	Write Memory by Address
3E	7E	Tester Present
83	C3	Access Timing Parameter
84	C4	Secured Data Transmission
85	C5	Control DTC Setting
86	C6	Response on Event
87	C7	Link Control

3.4.8 OBD SID/PID examples

The following table gives some examples of combinations of service IDs and parameter (Wikipedia, 2020a). The information that can be requested has to be calculated on base of the given formula and the given unit and needs to consider the number of bytes that are specified.

Table 3.16: Example SID/PIDs

SID	PID	Bytes	Description	Min	Max	Unit	Formula
01	0C	2	Engine RPM	0	16,383.75	rpm	(256*A+B)/4
01	0D	1	Vehicle Speed	0	255	km/h	A
01	11	1	Throttle position	0	100	%	A*100/255
01	22	2	Fuel Rail Pressure (relative to manifold vacuum)	0	5,177.265	kPa	(256*A+B)*0,079
01	3C 3D 3E EF	2	Catalyst Temperature Bank: 1;2 Sensor: 1;2	-40	6,513.5	°C	(256*A+B)/10-40
01	5E	2	Engine fuel rate	0	3,212.75	L/h	(256*A+B)/20
01	7C	2	Diesel Particulate filter (DPF) temperature	-40	6,513.5	°C	(256*A+B)/10-40
03	-	n*6	Request trouble codes				3 codes per message frame
04	-	0	Clear trouble codes / malfunction indicator lamp (MIL) / check engine light				Clears all stored trouble codes and turns the MIL off.
09	02	17	Vehicle Identification Number (VIN)				17-char VIN, ASCII-encoded and left-padded with null chars (0x00) if needed to.

3.4.9 Diagnostic Trouble Codes (DTC)

Service ID 03 requests *Diagnostic Trouble Codes (DTC)*. In case there are one or two trouble codes that are responded, they will be encapsulated in an ISO-TP single frame, in case of more than two DTCs, first plus consecutive frames are used as needed.

Each trouble code consists of two bytes that are displayed as 5 characters. The first character represents the *Trouble Code Sub System* which describe which sub-system of the car is affected (character P, C, B or U), the *Type of Code* shows if the code is standardized (=0) or vendor specific (=1), the *Affected Sub System* as a hexadecimal character, and the *Specific Code* of the specific trouble as a two-digit hexadecimal number.

A7..A6	A5..A4	A3..A0	B7..B4	B3..B0
trouble code sub-system	type of code	affected sub-system	specific code	
0: P - Powertrain 1: C - Chassis 2: B - Body 3: U - Network	0: Generic OBD (ISO/SAE) 1: Manufacturer specific	1: Fuel and air metering 2: Fuel and air metering (injector circuit) 3: Ignition system or misfire 4: Auxiliary emission controls 5: Vehicle speed control and idle control system 6: Computer output circuit 7-9: Transmission system A-C: Hybrid propulsion	00-FF	

Figure 3-19: Structure of an OBD Diagnostic Trouble Code DTC

3.5 Utility, heavy-duty and commercial vehicles: J1939

Utility, heavy-duty and commercial vehicles, like trucks, tractors, or building machines differ to personal cars in several ways. Not only the size and composition of the vehicle is different, but also the different emission standards. The various extensions and additional tools, which are not present in passenger cars, make it necessary to use a specific standard. The standard that is widely used is the SAE J1939 standard, which differs in the use of the CAN bus in comparison to OBD/UDS in various ways. But in terms of functionality, there is a mapping between J1939 and OBD/UDS in regard to a core set of services.

Table 3.17: Standards of Trucks, Busses and Tractors in relation to OSI layers

<table>
<tr><th colspan="3" rowspan="2">OSI Layer</th><th colspan="2">Trucks and Bus</th><th colspan="2">Tractor with Trailers</th></tr>
<tr><th colspan="2">J1939</th><th colspan="2"></th></tr>
<tr><td>7</td><td colspan="2">Application Layer</td><td>SAE J1939-71
SAE J1939-73</td><td rowspan="11">SAE J1939-01
SAE J1939-81</td><td rowspan="2">ISO 11992-4</td><td rowspan="5">ISO 11992-2
ISO 11992-3</td></tr>
<tr><td>6</td><td colspan="2">Presentation Layer</td><td>SAE J1939-DA (SPN)
SAE J1939 Appendix C (SPN)
SAE J1939-73 Appendix A (FMI)</td></tr>
<tr><td>5</td><td colspan="2">Session Layer</td><td></td><td>ISO 14229-2</td></tr>
<tr><td>4</td><td colspan="2">Transport Layer</td><td></td><td rowspan="2">ISO 15765-2</td></tr>
<tr><td>3</td><td colspan="2">Network Layer</td><td>SAE J1939-31</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">Datalink Layer</td><td>LCC - Logical Link Control</td><td rowspan="2">SAE J1939-21</td><td colspan="2" rowspan="2">ISO 11898-1</td></tr>
<tr><td>MAC - Medium Access Control</td></tr>
<tr><td rowspan="4">1</td><td rowspan="4">Physical Layer</td><td>PLS - Physical Media Signalling</td><td rowspan="4">SAE J1939-11
SAE J1939-12
SAE J1939-14
SAE J1939-15</td><td colspan="2" rowspan="4">ISO 11992-1</td></tr>
<tr><td>PMA - Physical Medium Attachment</td></tr>
<tr><td>PMS - Physical Medium Specification</td></tr>
<tr><td>MDI - Medium Dependent Interface</td></tr>
</table>

3.5.1 Standards overview

The following table provides all parts of the SAE J1939 standard. For towing and towed vehicles, the specific standard ISO 11192 is in place which clarifies specific aspects of that type of vehicles. The structure of the standards if given in the second table.

Table 3.18: SAE J1939: Recommended Practice for a Serial Control and Communications Vehicle Network (US Standard - Truck and Bus)

SAE J1939: Recommended Practice for a Serial Control and Communications Vehicle Network (US Standard - Truck and Bus)	
Part 01	Recommended Practice for Control and Communications Network for On-Highway Equipment
Part 02	Agricultural and Forestry Off-Road Machinery Control and Communication Network
Part 03	On Board Diagnostics Implementation Guide

SAE J1939: Recommended Practice for a Serial Control and Communications Vehicle Network (US Standard - Truck and Bus)	
Part 05	Marine Stern Drive and Inboard Spark-Ignition Engine On-Board Diagnostics Implementation Guide
Part 11	Physical Layer – 250 kBits/s, Shielded Twisted Pair
Part 12	Physical Layer – 250 kBit/s, Twisted Quad of Wires and Active Bus Termination
Part 13	Off-Board Diagnostic Connector
Part 14	Physical Layer – 500kBit/s
Part 15	Reduced Physical Layer, 250 kBits/s, Un-Shielded Twisted Pair (UTP)
Part 21	Data Link Layer (CAN 2.0B)
Part 31	Network Layer
Part 71	Vehicle Application Layer
Part 73	Application Layer – Diagnostics
Part 74	Application - Configurable Messaging
Part 75	Application Layer - Generator Sets and Industrial
Part 81	Network Management Protocol
Part 82	Compliance - Truck and Bus
Part 84	OBD Communications Compliance Test Cases for Heavy Duty Components and Vehicles
DA	Digital Annex

Table 3.19: ISO 11192: Road vehicles - Interchange of digital information on electrical connections between towing and towed vehicles

ISO 11192 Road vehicles - Interchange of digital information on electrical connections between towing and towed vehicles	
Part 1	Physical and data-link layers
Part 2	Application layer for brakes and running gear
Part 3	Application layer for equipment other than brakes and running gear
Part 4	Diagnostic communication

3.5.2 J1939 messages on CAN

The J1939 message only uses a 29-bit CAN-identifier. In contrast to OBD, where the SID and PID are part of the data field, then equivalent *Parameter Group Number (PGN)* is part of the 29-bit identifier, which also contains the *Priority P* (0=high) and the *Source Address SA* of the message. As a consequence, only data that is specified by the PGN is provided in the data field. The values in the data field represent a set of *Suspect Parameter Numbers (SPNs)*, meaning, that often multiple parameters are provided and not only one value. The size of the data field and the assignment of bits to SPNs is predefined by the PGN (Junger, 2010; Ixxat, 2020; CSS Electronic 2020b).

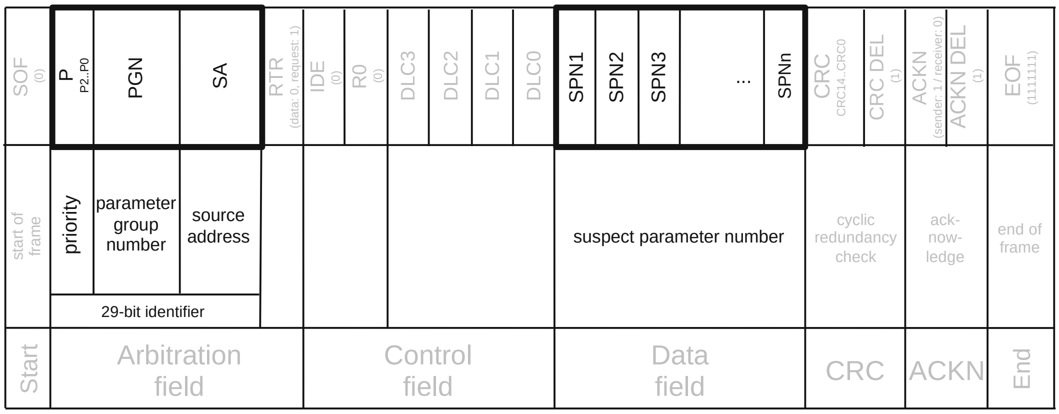


Figure 3-20: J1939 message on CAN

3.5.3 J1939 Identifier and Parameter Group Number (PGN)

The PNG is structured in three sections: The *Data Page (DP)* and the *Extended Data Page (EDP)* decide on which standard should apply for the structure of the 29-it identifier. J1939 based identifier are always with DP=0. The current version is given with EDP=0, while EDP=1 is reserved for future use. EDP/DP=01 describe NMEA2000 identifiers (maritime standard) and EDP/DP=11 describe ISO 11992 diagnostics-based identifier.

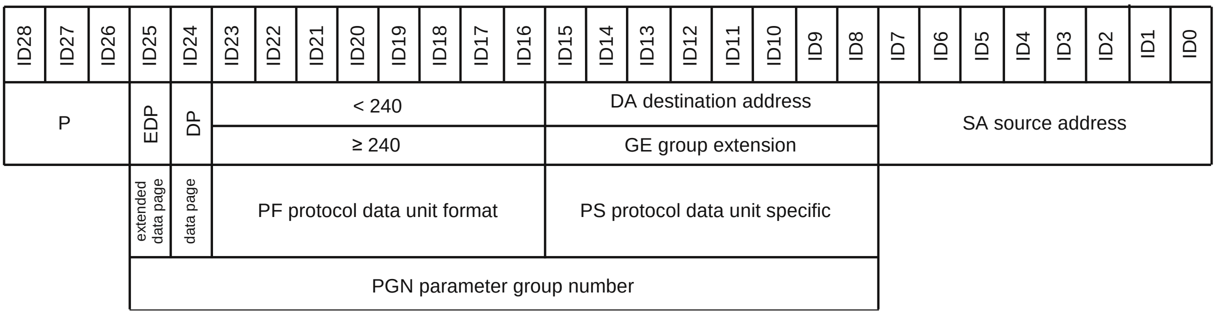


Figure 3-21: Structure of the 29-bit CAN identifier in J1939

The second part of the PGN specifies the *Protocol Data Unit Format (PF)*. The number that is given by the PF decides on the meaning of the third section, the *Protocol data unit specific (PS)*. In case this PF value is below 240, the PS part represents a *Destination Address (DA)*. This results in 240 parameter groups which are used to target specific addresses. In case the PF value is above or equal to 240, the PS part represents the *Group Extension (GE)*, and so these bits are part of the parameter group. For these 16*256=4096 parameter groups messages are broadcasted to all.

Messages that provide the data of SPNs are usually broadcasted via the CAN bus, but for some PGN, the values of the SPNs have to be requested. For this purpose, the special PGN 59904 exists that only contain the requested PGN as one SPN.

A subset of PGNs define *Diagnostic Messages (DM)*. They cover nearly all functionality, that is defined in the Unified Diagnostic Service UDS. In contrast to UDS, most of these messages are send autonomously and do not need to be requested.

3.5.4 J1939 PGN/SPN examples

The following table gives some examples of combinations of parameter group numbers and suspect parameter numbers as shown in Part 71 of SAE J1939. The information that can be requested has to be calculated on base of the given resolution and offset and the given unit. One has to consider the number of bytes that are specified.

Table 3.20: Example PGN/SPNs

PGN	SPN	Bytes	Description	Min	Max	Unit	Resolution, Offset
61444	190	2	Engine Speed	0	8,031.875	rpm	0.125 rpm per bit 0 rpm offset
65265	84	2	Wheel-Based Vehicle Speed	0	250.996	km/h	1/256 km/h per bit 0 km/h offset
65132	1624	2	Tachograph vehicle speed	0	250.996	km/h	1/256 km/h per bit 0 km/h offset
61441	523	1	Current Gear Position	-125	125		1 gear value/bit -125 offset
65257	182	4	Trip Fuel	0	2,105,540,607.5	L	0.5 L/bit 0 L offset
65266	183	2	Fuel Rate	0	3,212.75	L/h	0.05 L/h per bit 0 L/h offset
65266	51	1	Throttle Position	0	100	%	0.4% per bit 0% offset
65263	100	1	Engine Oil Pressure	0	1000	kPa	4kPa per bit 0 kPa offset
61450	132	2	Inlet Air Mass Flow Rate	0	3,212.75	kg/h	0.05 kg/h per bit 0 kg/h offset
65262	179	2	Turbo Oil Temperature	-273	1735	°C	0,03125 °C per bit -273 °C offset

3.5.5 Diagnostic Trouble Codes (DTC)

In case of errors, *Diagnostic Trouble Codes (DTC)* will be sent that describe an abnormal state of SPNs. It consists of the erroneous SPN, a *Failure Mode Identifier (FMI)* that describes the kind of error that has happened, and the *Occurrence Counter (OC)* that tells how often the error has occurred. The one bit that describes *Conversion Method (CM)* of the SPN is used to tell if the SPN is provided with least significant bit first (=0, intel method) or the other way around.

<table>
<tr><td colspan="3">SPN</td><td>FMI</td><td>CM</td><td>OC</td></tr>
<tr><td colspan="3">suspect parameter number</td><td>failure mode identifier</td><td>conversion method</td><td>occurrence count</td></tr>
<tr><td colspan="3">19
bit</td><td>5
bit</td><td>1
bit</td><td>7
bit</td></tr>
<tr><td>Byte 1</td><td>Byte 2</td><td colspan="2">Byte 3</td><td colspan="2">Byte 4</td></tr>
</table>

Figure 3-22: Diagnostic Trouble Code structure inside the CAN data frame

4 Performance of OBD in detecting malfunctions

Vehicles that are poorly maintained or malfunctioning are important contributors to air pollution. The goal of an inspection and maintenance (I/M) program is to ensure that vehicles remain safe, in good working order throughout their lifetime, and do not produce excess pollution (Posada et.al., 2015). At the core of an I/M program is the requirement that vehicle owners regularly submit their vehicles for a standardized inspection (Shambliss et.al., 2016). If the vehicle fails inspection, it needs to be repaired and re-inspected before it returns to normal operation.

Recently manufactured vehicles are equipped with an OBD II. OBD II monitors all engine and drive train sensors and actuators for shorts, open circuits, lazy sensors and out of range values as well as values that do not logically fit with other power train data. Thus, OBD II keeps track of all of the components responsible for emissions and when one of them malfunctions, it signals the vehicle owner by illuminating a Maintenance Indicator Lamp (MIL), Such as a check engine indicator. It also stores Diagnostic Trouble Codes (DTCs) designed to help a technician find and repair the emission related problem (Webster et al., 2007). OBD II also specifies the means for communicating diagnostic information to equipment used in diagnosing, repairing and testing the vehicle.

International experience with integrating OBD into I/M procedures to detect malfunctions comes mainly from the United States. The U.S. Environmental Protection Agency (EPA) sets guidelines for states to follow in designing and running I/M programs as per the 1990 amendment to the Clean Air Act. These guidelines mandate that OBD checks be integrated into any state's I/M program for light-duty vehicles and specify a seven-step check procedure that should be followed (U.S.EPA, 2001). Because OBD system requirements for heavy-duty vehicles were not specified at the time of the amendment, OBD checks were not mandatory for heavy-duty I/M programs in the United States. However, states have requested additional guidance for heavy-duty OBD checks, and EPA has acknowledged the possibility that there may be guidelines proposed in the future for heavy-duty OBD in I/M programs (U.S.EPA, 2005). South Korea has designed its light-duty OBD system requirements to include anti-tampering features so that I/M programs can rely on OBD checks (Posada & German, 2016). Few other countries with mature I/M programs have fully integrated OBD checks; among the members of the European Union, only the Netherlands includes OBD checks, and the I/M program guidelines in Japan do not specifically include OBD checks.

EPA does not recommend that vehicles older than 1994 be subjected to OBD based I/M testing, even if it is determined that the vehicle is equipped with an OBD computer, "On-board diagnostic test procedures" requires that the scan tool used for the OBD-I/M inspection be capable of communicating with the OBD system in compliance with the Society of Automotive Engineers (SAE) Recommended Practice J1979. While it is possible to perform the electronic scan portion of the OBD-I/M check in the KOEO position for most vehicles, EPA discourages this practice because it can lead to false failures for some makes and models of vehicles (such as 1996-2001 Subarus) and may even have a malfunction indicator light (MIL) illuminated (U.S.EPA, 2001) [7]. The reason for not performing an OBD-I/M scan on pre-1994 OBD-equipped vehicles is because such vehicles use an earlier, non-standardized generation of OBD system (also known as OBD I). Due to the lack of federal standards for OBD I systems, the systems themselves tend to be proprietary and may not be compatible with the standardized OBD II scanners that will be used in most I/M programs.

Today, the available diagnostic information through OBD has considerably been improved, as its introduction dates back to the early 1980s. The modern OBD systems have become more sophisticated and now adopt a standardized digital communications port to provide real time data in addition to a standardized series of diagnostic trouble codes, (DTCs), which allow one to quickly identify and repair malfunctions within the vehicle, as it provides almost complete control and also monitors parts of chassis, body and accessory devices as well as the diagnostic control network of the vehicle (Medashe et.al., 2020).

In OBD I/M/ inspection Process the inspector connects the inspection workstation to the vehicle's on-board computer, and then downloads engine and emissions control data (MODULE4). The work-station checks several OBD system functions:

- Communication. Does the vehicle's OBD system communicate with the workstation? If the vehicle's OBD system cannot communicate with the station's workstation, the OBD system must be repaired before the emissions test can proceed.
- Readiness. Is the vehicle's OBD system Ready to be tested? As the vehicle drives, the OBD system checks the performance of various emissions-related components and systems. If the OBD system has not performed enough of these self-checks, the vehicle is Not Ready for an emissions test.
- Diagnostic Trouble Codes (DTCs). If the OBD system has detected an emissions-related problem, it will turn on the Check Engine light and store one or more DTCs that indicate which systems or components are not performing as designed. Reviewing these codes is the first step in diagnosing an emissions-related problem. These codes, along with other information in the OBD system, can guide emissions repair technicians to a proper diagnosis.

Today due to the importance of I/M programs for air pollution, many researches have been performed on this area providing variable patents and methods to improve inspection. Thomas Webster et al. (2007) developed an invention which includes a vehicle device that monitors the status of the I/M readiness monitors to determine if the vehicle is "Ready" for an emissions test. The device will indicate to a driver that the vehicle is ready for emissions testing by alerting the user via, for example, audio and/or visual signals or other alert indicators. Checking the readiness state of the diagnostic monitors allows a driver to save time by not having to return the vehicle for testing only to find out that the vehicle is still not ready for emissions testing. (Jhou & Chen, 2014), proposed a system which is integrated with OBD-II, 3.5 G wireless network, and cloud computing technologies. It can perform real time vehicle status surveillance. The monitored features cover engine rpm, vehicle speed, coolant temperature, fault codes, and other vehicle dynamics information. The vehicle information will be transmitted to the cloud computing server via 3.5 G wireless network for fault analysis. Once cloud computing server detects fault conditions, the proposed system could classify the fault conditions depended on vehicle type and its model year. Then the cloud computing server will report the fault code analysis results to the user and provide the description about repair procedure. The proposed system will greatly shorten the time to detect vehicle trouble condition.

To conclude, OBD checks could be substituted for emissions testing requirements in alternating years, or for several consecutive years. During early stages of implementation, inspections including emissions testing should concurrently collect OBD data to ensure that results agree, and vehicles failing emissions tests would not pass inspection based on OBD alone. OBD check procedures should include measures to prevent fraudulent practices, including connecting the scanning tool directly to the vehicle and computer so the inspector cannot modify data during the inspection and ensuring that the vehicle identification number is reported in the OBD data so that it can be matched to the vehicle being inspected. Vehicles should also be required to display the readiness indicator during testing to ensure that any error codes have not been recently cleared. Once OBD checks have been demonstrated to be effective, they can be increasingly substituted for emissions testing.

From all the above, it is observed that as part of environmental policies, numerous states require that vehicles undergo periodic emission testing to ensure that vehicles registered in US states comply with mandated emission requirements, which emission testing may be performed utilizing a vehicles OBD system. Vehicles that do not meet the requirements may not qualify for registration until repairs are made and may be subject to fines. However, vehicles may be improperly tampered with to circumvent such detection. For example, vehicle owners or service companies may alter vehicles in efforts to increase the performance of the vehicles, such as removing catalytic converters or the catalysts from the converter, which alterations negatively impact the vehicles emissions. As part of such modifications, the vehicle may be altered or tampered with to prevent detection of such modifications, such as by changes to the engine computer and/or OBD System sensors.

Tampering with, or illegally modifying, emission control devices can substantially distort a fleet's impact as only a few high emitting vehicles with improperly working/removed emission control devices can be held responsible for disproportionally high contributions to poor local air quality [11]. Whereas tampering with diesel particulate filters is mostly applied on light-duty vehicles, deactivating de-NOx systems like selective catalytic reduction (SCR) systems generally occurs in the heavy-duty sector. Nonetheless, as SCR technology is deemed to become the reference in light-duty diesel vehicles, it's only a matter of time before consumers try to bypass such systems. The impact of these measures is unambiguous, as a removed particle filter increased particle emissions number by a factor thousand, while heavy-duty de-NOx bypassing increases NOx emissions by a factor 4 to 20 for Euro VI technology (Hooftman, 2019).

Motives for tampering are diverse. Firstly, there's the perceived monetary gain of saving AdBlue® expenses and the avoided maintenance. Secondly, there's the emission test during periodic technical inspection, which often is incapable of detecting tampering. Lastly, there's the perceived lack of enforcement against it.

Some defeat devices and tampering examples are listed below (Avedo & Yarbrough, 2019):

- Alterations to Fuelling, Timing Strategy
- DPF Delete
- EGR Delete
- SCR Delete
- Alterations to OBD
- Software and Hardware

One important means to monitor the performance of emission control devices with which every light- and heavy-duty vehicle in both regions and the EU is equipped, is the onboard diagnostics system (OBD). This technology is designed to perform a diagnostic monitoring of components that are part of a vehicle's emission control system and to detect situations that could lead to high emissions. Thus, it serves as an interface between the vehicle and its driver to report issues and urge repair, while at the same time it allows the repairer to diagnose engine and after-treatment related problems. Moreover, OBD serves as a key indicator for a vehicle's maintenance level during PTI and throughout the vehicle's lifetime. Besides the lack of monitoring requirements, the Europe OBD system is not robust enough when it comes to tampering. Crucial threats to the current system are that data trouble codes (DTC) can be cleared using low-cost communication tools, while new software can be loaded into the engine control unit (ECU) to increase power and to disable EATS functionalities to alter the system in such a way that it avoids DTCs. Several measures are taken to prevent such practices, including permanent DTCs, readiness codes, and the combination of calibration ID and calibration verification numbers. DTCs are generated when a malfunction occurs in one of the systems that are monitored by OBD. In this case, the driver will be warned when something is wrong via a dashboard malfunction indication. Both the California OBD II and Korea OBD have clear requirements for storing DTCs permanently, offering a better protection against clearances and thus providing a much better technical support for PTI purposes based on OBD. The Europe OBD system, however, lacks this fundamental possibility. One way to work around this flaw in current Europe OBD legislation is by remote exchange of emission data and/or DTCs or monitoring them onboard.

Complementary to the permanent DTCs, readiness bits indicate the status of the ten most important monitored systems. These bits will indicate when a certain monitor has not yet finished a complete diagnostics cycle which can result in a failed PTI in California, in case a permanent DTC indicates an underlying problem. If no such DTC was stored, the incomplete cycle might refer to a recent repair during which the battery was disconnected. This back-up is not available in case for Europe OBD, although it would not make sense for vehicle owners to erase the readiness bits as this could also lead to a failed PTI (depending on if Europe OBD is applied complementarily to the emission test). Instead, the vehicle owner could simply have all non-permanently stored DTC erased.

A last measure that the California OBDII and Korea OBD have against tampering is to download the running calibration ID (CAL ID) number from the inspected vehicle and to compare this to a national database containing the possible combinations with the calibration verification number (CVN). This allows for the detection of non-original ECU software and thus tampering if it does not come with an approval certificate issued by an accredited lab. This approach, however, requires all vehicle manufacturers to provide the regulators with every available CAL ID/CVN combination, for them to keep the database continuously up to date. One pitfall of this approach is that the correct CAL ID can be re-flashed into the ECU solely to pass PTI, to be reset afterwards. Also here, opportunities arise for remote transmission of a vehicle's CAL ID. The European OBD program requires CAL IDs to be made available via the Europe OBD data link connector but does not mention any requirements on CVN.

Today, many researches have been performed on this area providing variable patents and methods against tampering. The authors of (Geilen et al., 2014), developed a vehicle testing system which is directed to vehicle testing, and in particular to a method and apparatus for detecting whether an on-board diagnosis system of a vehicle has been improperly tampered with or altered. The present invention provides a method and system for detecting whether a vehicle has been improperly tampered with to prevent detecting that the vehicle does not comply with vehicle regulations by detecting improper modification of a vehicle via the vehicles on-board diagnosis system.

As it is observed, the issue of vehicle tampering is of outmost importance and only through strong legislation, issued through European Regulations, and the implementation of effective enforcement against tampering, will consumers and companies no longer be tempted to illegally modify their vehicles. Tampering is being addressed in Tasks 2.5 and 3.4 of this project and will be reported in D2.3 and D3.1.

5 Potential impact of retrofits

5.1 Analyse existing field data from retrofitted buses and trucks, real world emission reduction potential

5.1.1 Objective of the work

The goal of this work is to research how different factors, environmental or mechanical, affect the function of their retrofitted emission after-treatment system. The purpose of the retrofit system is to reduce the emissions in exhaust gases and upgrade a vehicle to achieve the latest emission standards. The European emission standards are studied and opened for gaining a more accurate picture of the objective for a correctly working EAT (exhaust after-treatment) system.

The studied data has been collected from vehicles which have been retrofitted with Proventia's EAT system consisting of DPF and SCR. In the EAT system exhaust gases flow through DOC, DPF and SCR and achieved emission values will be collected from variable vehicle sensors. The used data in this thesis has been collected by a NO_x emissions monitoring system called PROCARE Drive. The system collects live data from the vehicles with the retrofitted EAT system and uploads the information online.

The aim was on finding factors in different vehicle categories which cause EAT system to work inefficiently. Because of the large amount of collected data and the fact that the information has not been categorised in any clear order, emission readings had to be tabulated for more precise analysis. To find connections between actual emission readings and mechanical or environmental factors multiple vehicle characteristics had to be sorted out too. It was expected that studying the data would reveal some phenomena that affect the EAT system operation negatively.

5.1.2 Test Procedures

Low emission adaptations must be tested to meet the technical performance requirements. Buses must be tested at kerb weight plus driver weight and one quarter of the specified total passenger load using a weight of 68 kg per passenger, or half of the specified seated passenger load using a weight of 68 kg per passenger, whichever is judged by the technical service to be the worst case for effective performance of the retrofit system. (CVRC, 2019)

Buses operating in the UK must be tested according to the LowCVP UK Bus (LUB Revised) cycle, which is shown in Figure 5-1. To warm the vehicle up prior to testing, only the Outer-London phase shall be used. (CVRC, 2019)

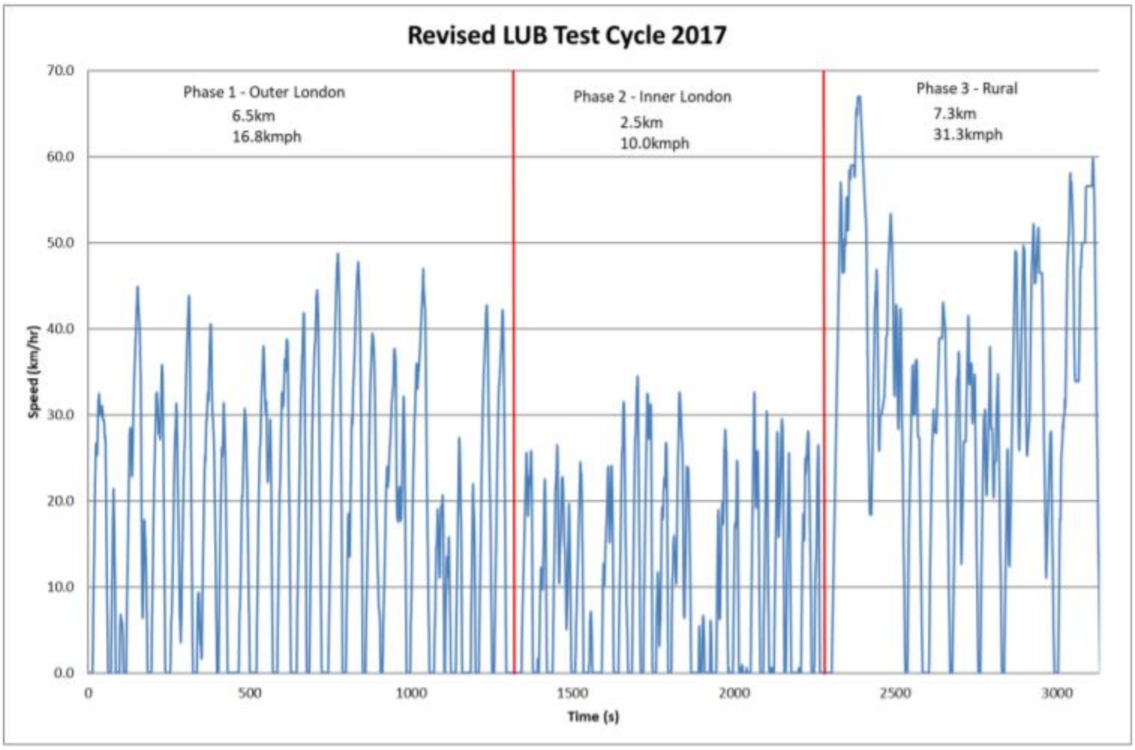


Figure 5-1: Revised LUB Test Cycle 2017 ***(CVRC, 2019)***

Applied emission limits for the test cycle are presented in Table 5-1.

Table 5.1: Emission limits applying to buses ***Source: (CVRC, 2019)***

Exhaust emission parameter		Maximum permitted limit	Reduction performance
Primary emissions			
Mixed oxides of nitrogen	NOx	500mg/km	>80%
Nitrogen dioxide	NO_2	100mg/km	
Particulate matter (PM)	PM	10mg/km	
Number of particles (PN)	PN	6 x 10^{11}/km	
Secondary emissions			
Nitrous oxide/methane	N_2O/CH_4 (as CO_2e)	< 5% of CO_2	
Carbon dioxide	CO_2	< 1% increase	
Ammonia	NH_3	10ppm average 25ppm peak	
In service			
Mixed oxides of nitrogen	NOx		> 80% daily average

Evaluation criteria for NO_x reduction systems with increased reduction performance for buses operating in Germany are different. The emissions are measured on-route with PEMS-testing and the emission limits are divided by a speed class (Federal gazette, 2018). Classified route related emissions can be seen from Table 5-2.

Table 5.2: Classified route-related emissions

Speed class (km/h)	Speed range (km/h)	Limit (g/km)
10	7.5 - 1.,5	7.5
15	> 12.5 - 17.5	5
20	> 17.5 - 22.5	4
25	> 22.5 - 27.5	3
30	> 27.5 - 32.5	2.5

In addition to the route-related emissions, The NO_x reduction efficiency must be >85% and the EAT system must include ammonia slip catalyst with minimum volume of 800ml per 100kW engine power (Federal gazette, 2018).

5.1.3 Emission Monitoring & Data Collection

Emission monitoring in Proventia's EAT system has been implemented by using telematics. Telematics is a general term that refers to any device combining telecommunications and informatics. It includes controller, PROCARE Drive-unit which is connected to vehicle's CAN bus. The controller unit is equipped with GSM and GPS antennas to enable the place routing. Real time information about the back pressure, exhaust gas temperature, NO_x levels, AdBlue level and temperature and dosing rate is transmitted to the web service, where operators can monitor their fleet's emission readings. (Proventia, Procare Drive.)

To collect the needed information, variable sensors such as temperature, backpressure, NO_x and mass air flow sensors must be installed. Exhaust temperature is measured from the inlet side of the SCR. Exhaust gas pressure information is collected and transmitted to PROCARE Drive by using CAN bus pressure sensor which is connected to the pipe before DOC with flexible metal tube. In order to find out the NO_x reduction, two NO_x sensors must be installed. First one is connected to the inlet side of DOC to measure the NO_x in exhaust gases before the EAT system and the second measures NO_x amount after the EAT system from outlet pipe of the SCR. MAF information is received from CAN or from sensor. MAF (Mass Air Flow) sensor is installed to the pipe between air filter and turbocharger. Operating principle of Proventia's NOxBUSTER EAT system is described in Figure 5-2.

5.1.4 Data processing & research methods

The work was started by thinking of measures that could be needed in analysing the achieved emission readings. After the planning was done, daily reports were exported from Procare drive. The exported files included daily values for about 2000 vehicles from start of 2019 to end of October 2019. Before the actual analysis could be started, the received data needed to be processed to a readable form because all the exported files were in Excel Comma Separated Value (CSV) format. The main tool in processing the data was Excel's Power Query add-in. Power Query allowed to combine all the received data files in one and to format the data in clear order. Each row in the data shows daily averages for certain fleet numbers. Among other things the data included values for the NO_x in and out in ppm and mg/s, reduction efficiency, MAF, SCR inlet temperature and urea dosing amount.

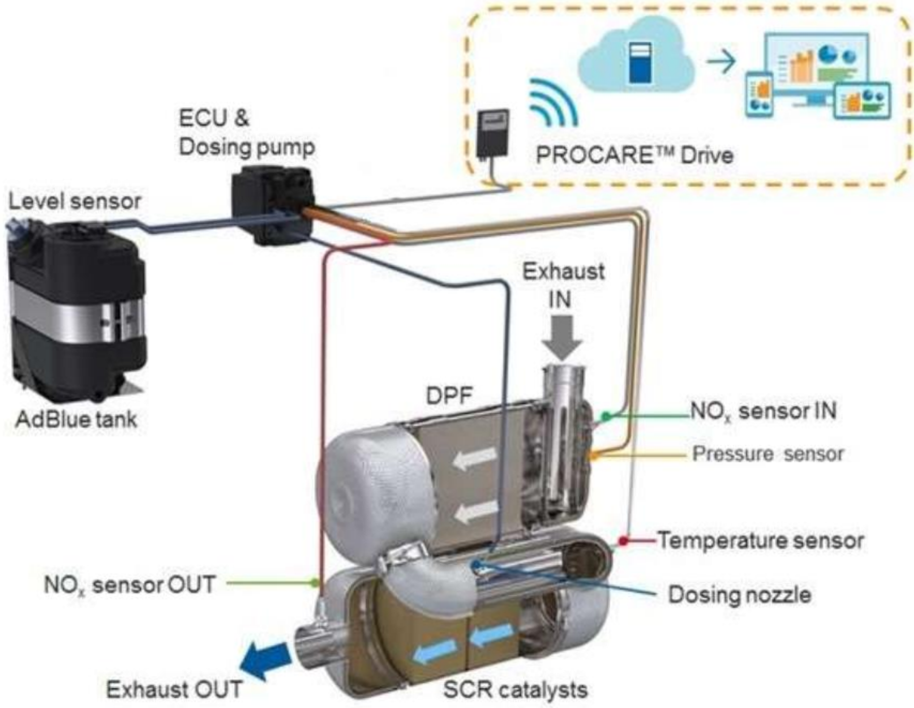


Figure 5-2: Operating principle of NOxBUSTER City system

To investigate the function of the retrofitted EAT system in different vehicles the Procare data had to be combined with vehicle information. Power Query enabled combining the Procare data with vehicle information by matching fleet numbers from different excel files that included information such as chassis make and model.

Considering that there were hundreds of thousands of rows information, some incorrect or missing values were involved. To gain a picture of how the EAT system is working in different type of vehicles and what emission values have been achieved, rows which did not have data, or the values were inaccurate i.e. because of broken NO_x sensor were removed. The data export included columns which stated daily running time of the system and travelled distance. It was noticed that g/km emission readings were excessively high on rows where the running time was low or travelled distance was not recorded for some reason. To ensure that only data where the EAT system was running and the vehicle has been on route was included, rows where the running time was less than 3600 seconds, or the travelled distance was under 10000 meters were filtered out.

The data also included a column which stated the ignored rows of MAF and NO_x sensors. This value is increased if there is no signal detected from the sensors for some reasons. Rows where the ignored rows exceeded half of the counted rows value were filtered out. In some cases, the intake manifold pressure sensor was down and messed up the calculation of MAF causing values to get excessively high. Because of this, filtering in MAF values had to be done.

The data did not include daily average speeds and engine-out NO_x emissions in g/km and therefore, they had to be calculated in custom columns. The custom column calculations were comparatively easy to complete with Power Query. The speed was calculated by using the running time of

In the research, the aim was on finding factors that affect the NO_x emissions and reduction efficiency of the EAT system. To gain a large picture of the bus fleet the count of different type of buses and engines were sorted out. NO_x reduction efficiencies for all the manufacturers and bus models were presented to reveal the differences in EAT system operation between different models. Engine-out NO_x emissions for engine types were presented to analyse the correlations between the engine design and emissions.

The effects of operating conditions were studied by comparing the average operating speed to the emitted NO_x and exhaust temperatures. Also, the exhaust temperatures were compared to the ambient temperature on a monthly level. The comparisons between operating speed and emissions were made to see if the increase in speed has a significant effect on emissions. As the SCR temperature is a huge factor in the catalyst operation, it was hoped to see if the ambient temperature and operating speed affect the exhaust gas temperatures.

5.1.5 Results

When the data was processed in readable form, additional filtering in Pivot could be used to select the vehicles to be studied. For example, only vehicle models with over eight units would be included in studied data. As additional filtering was done, results were presented using data-based tables and graphs.

The studied data contained information from 266 articulated buses, 950 double-deckers and 457 solo buses with retrofit EAT system. Body types from different manufactures and count of buses is shown in Table 5-3.

Table 5.3: Count of buses by body type & manufacturer

Body type	Manufacturer	Count, n	Total, n
Articulated	MAN	143	266
	Mercedes-Benz	123	
Double-decker	ADL	325	950
	Volvo	241	
	Wrightbus	301	
	VDL	83	
Solo	ADL	284	457
	MAN	60	
	Mercedes-Benz	81	
	Wrightbus	18	
	VDL	14	

Also, the engine types and properties for engines were defined. Properties and count of the buses by engine type is presented in Table 5-4.

Table 5.4: Properties & population for engine types

Engine	Euro class	Count, n	Original EAT	EGR
Cummins ISBe 4,5	IV	90	SCR	-
	V	184	SCR	-
Cummins ISBe 6,7	IV	21	SCR	-
	V	308	SCR	-
OM906 hLA	V/EEV	31	SCR / SCR + DPF	-
OM457 hLA	V/EEV	162	SCR / SCR + DPF	-
Volvo D9	IV	3	SCR	-
	V	184	SCR	-
Volvo D5E/D5F	V	54	SCR	-
D2066 LUH	IV	52	PM-Kat	X
	V/EEV	123	CRT	X
D2866 LUH	III	8	EGR	X
	IV	3	PM-Kat	X

To see a wider picture about function of the EAT system, first it would be wise to compare the efficiency between different manufacturers and models. As seen in Figure 5-3, clearly, the best efficiency is achieved within MAN and Mercedes-Benz.

Row Labels	Distinct Count of Fleet Number	Average of NOx reduction efficiency from ppm (%)
Volvo	242	81,3
Wrightbus	319	82,1
VDL	97	86,4
ADL	609	86,5
Mercedes-Benz	204	92,6
MAN	203	93,0
Grand Total	1674	86,3

Figure 5-3: Vehicle count and average NOx reduction efficiency by manufacturer

The filtering within models to show vehicles with eight units or more was chosen to include both Wrightbus Streetlite models. Efficiencies between different models are shown in Figure 5-4.

Row Labels	Distinct Count of Fleet Number	Average of NOx reduction efficiency from ppm (%)
Volvo		
B5LH	54	79,7
B9TL	188	81,5
Wrightbus		
Streetlite DF	10	70,0
NRM	301	82,1
Streetlite WF	8	89,5
VDL		
Citea LLE-120	14	85,3
DB300	83	86,7
ADL		
Enviro 400H	79	73,5
Enviro 200	284	83,4
Enviro 400	246	91,5
Mercedes-Benz		
CITARO O530 OM457	16	86,6
CITARO O530 OM457 WO DPF	13	87,2
CITARO O530 G OM457 WO DPF	68	87,9
CITARO O530 OM906 W DPF	30	95,0
CITARO O530 OM457 W DPF	22	95,0
CITARO O530 G OM457 W DPF	55	95,2
MAN		
LION´S CITY NG323	24	83,1
LION´S CITY A21 D20 E4	10	89,8
LION´S CITY A40 D20 E5	11	92,3
LION´S CITY A23 D20 E5	61	92,8
LION´S CITY A23 D28 E3	8	93,6
LION´S CITY A21 D20 E5	50	93,9
LION´S CITY A23 D20 E4	39	94,8
Grand Total	1674	86,3

Figure 5-4: NOx reduction efficiency by vehicle model

5.1.6 NO_x Emissions & Reduction Efficiency

The recorded emission readings were initially studied on a large scale based on the original emission class and number of axles. Average NO_x emissions for 2-axle buses presented in Figure 5-5 and 3-axle buses in Figure 5-6.

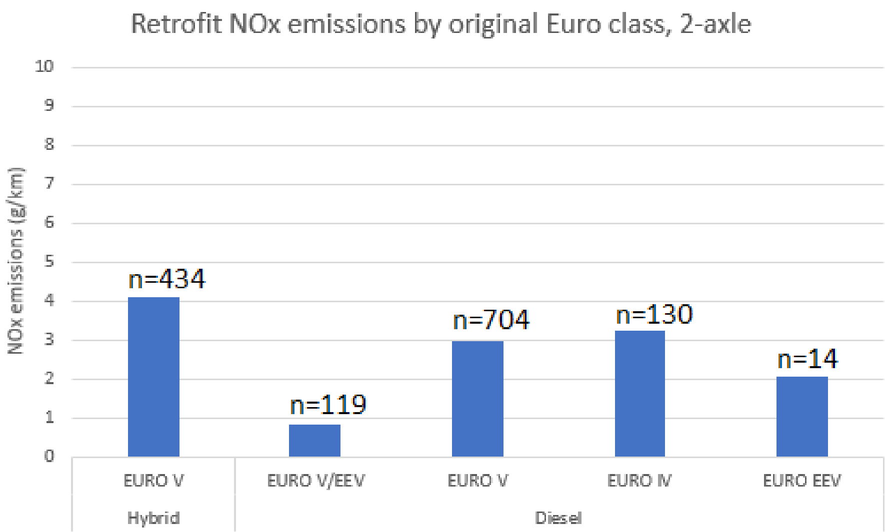


Figure 5-5: Achieved NOx emissions for 2-axle buses (Average of all buses)

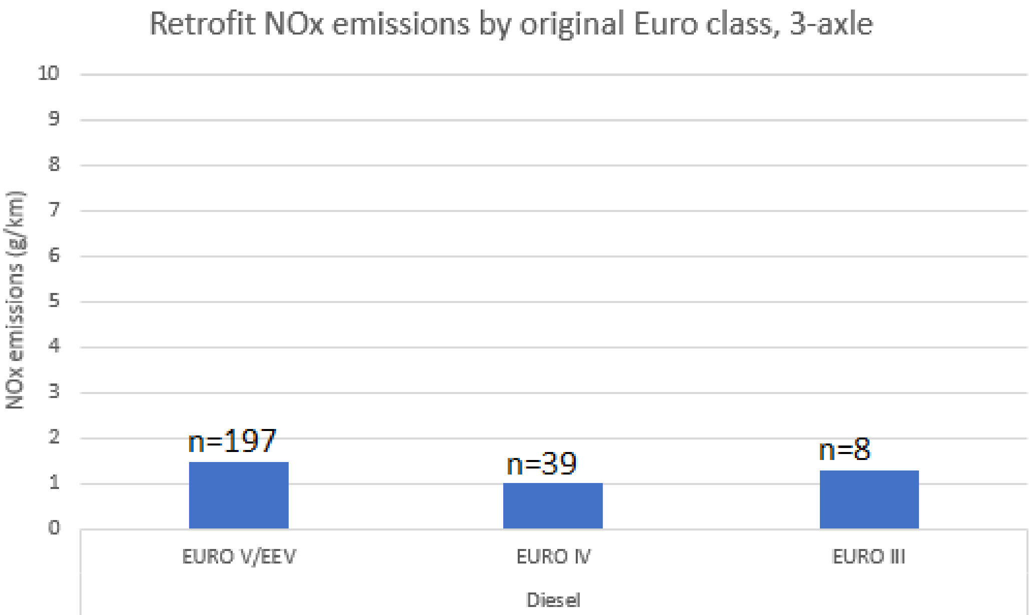


Figure 5-6: Achieved NOx emissions for 3-axle buses (Average of all buses)

Emissions for vehicles divided by body type are seen on Figure 5-7.

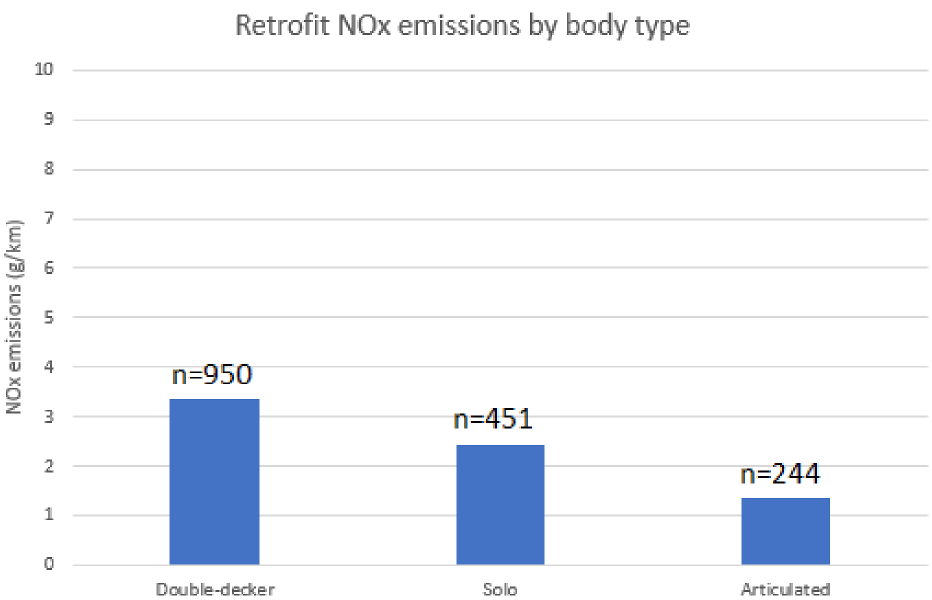


Figure 5-7: Achieved NOx emissions by body type

The average NO_x reduction efficiencies during the period from January to October were compared between the models with the best and the worst reduction efficiency. Figure 5-8, where n=count of included vehicles, reveals that the EAT in MAN and Mercedes buses functions in great efficiency about 95% while the bottom end is working with little over 80% efficiency. Figure also shows that the vehicles with worst efficiency are equipped with Cummins and Volvo engines, therefore closer inspection of engines' NO_x emissions and design is needed.

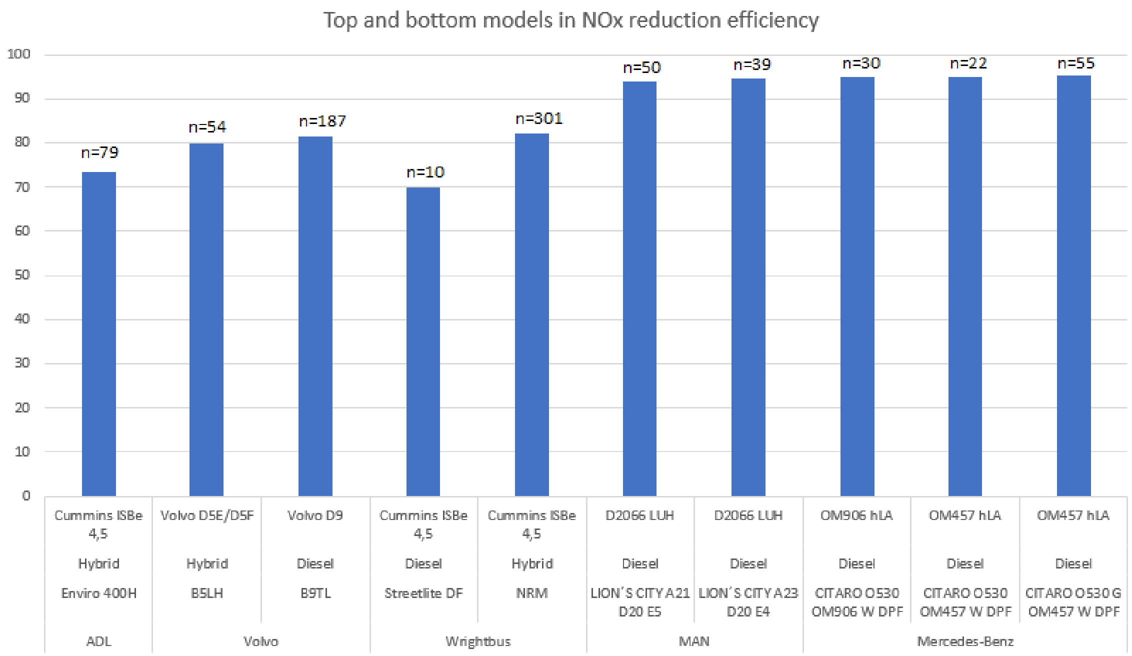


Figure 5-8: Top and bottom models in NOx reduction efficiency

As engine emissions were compared, Volvo and Cummins engines generated notably higher NO_x emissions in combustion process than the rest. Raw engine-out emissions by different engine types and count of buses are presented in Figure 5-9 below.

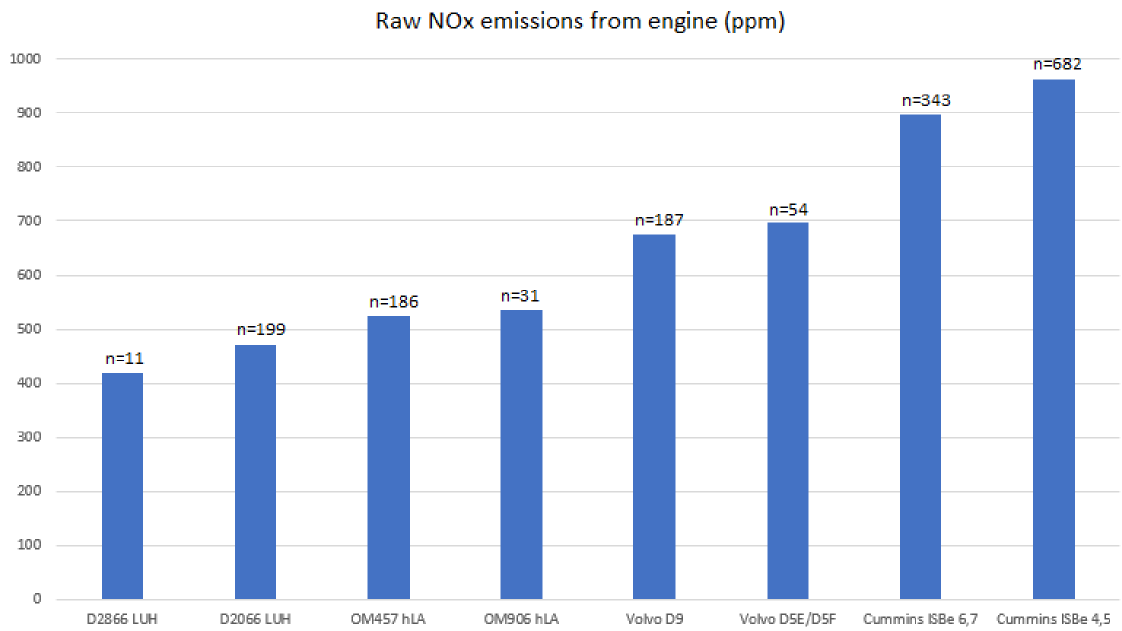


Figure 5-9: NOx emissions before EAT (engine out NOx)

Figure 5-10 represents the NO_x emissions within the vehicle models with the best and the worst reduction efficiencies on a four-month period from July to September. Orange beams indicate the raw engine-out NO_x emissions, grey beams show the tailpipe emissions after the EAT system and the blue line is reduction efficiency.

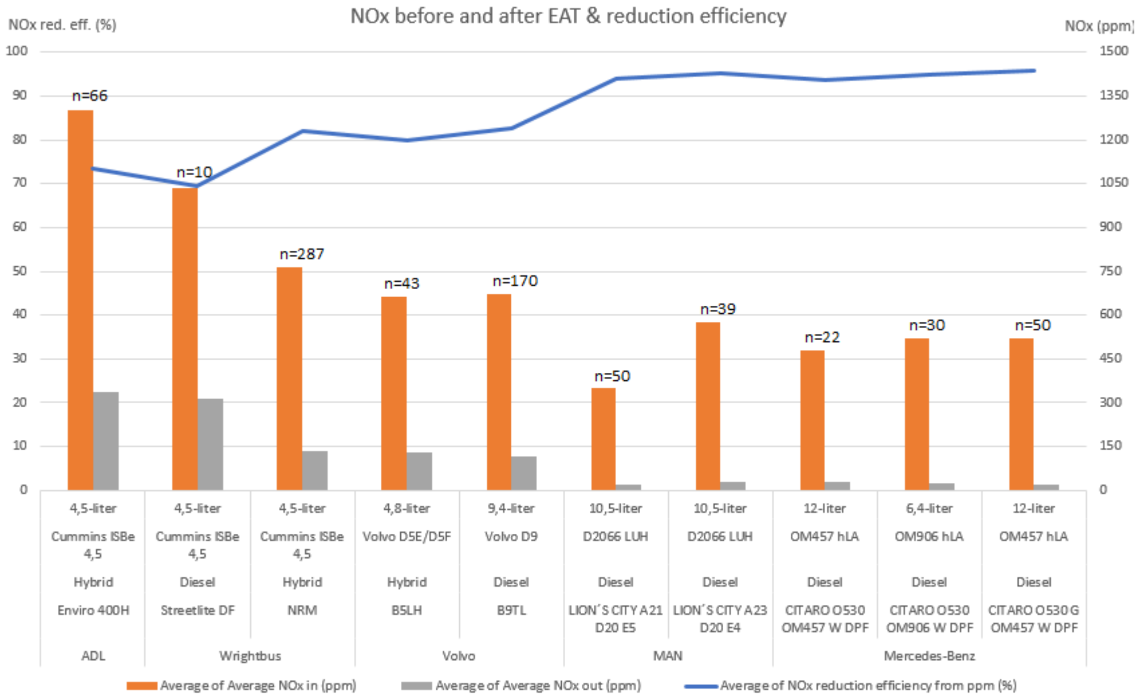


Figure 5-10: NOx emissions before and after EAT

Figure 5-10 shows that three out of five bottom models are hybrids, and there is significant difference in NO_x emissions between Enviro 400H and NRM, although both models use series hybrid technology and the same Cummins' engine.

To see a picture of emissions during driving, comparison of emissions over the travelled distance was done. NOx emissions in grams per kilometre for the same vehicle models are shown in the Figure 5-11. Buses with Cummins, Volvo and Mercedes engines have been originally equipped with SCR catalyst.

The graph 5-11 shows average NO_x emissions in g/km before and after the EAT for different vehicles. Green arrow on the right side of the picture represents the estimated scale of achieved emissions with the original SCR, in this case for buses with Cummins, Volvo and Mercedes engines. The estimation is based on research results, where various Euro III, IV, V and EEV buses were tested on Braunschweig, Helsinki2 and Helsinki3 test cycles (VTT Research Notes, 2007 & City bus performance evaluation, 2019). The researches were conducted by VTT Technical Research Centre of Finland, which is a state owned and controlled non-profit limited liability company.

Comparing the emissions over the travelled distance reveals that the reduced amount of NO_x is nearly same between some models even the reduction efficiency and the emissions from tailpipe vary a lot. Figure 5-12 shows the average amount of reduced NO_x emissions in distance of one kilometre for these bus models.

By looking at the reduced grams of NO_x per kilometre, it can be noted that the amounts between buses with best and worst NO_x reduction efficiencies are quite similar. For example, Citaro O530 G and B9TL have both reached average reduction of slightly over 18 g/km even the reduction efficiency in Citaro is notably higher.

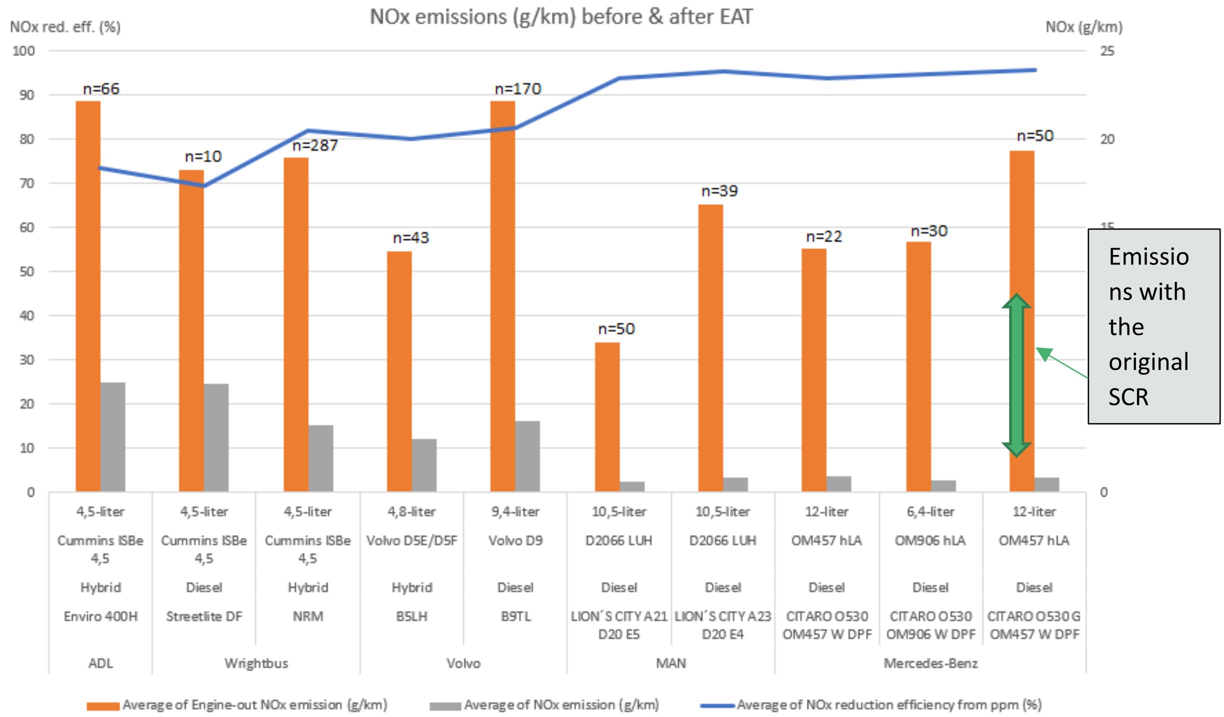


Figure 5-11: NOx emissions in grams per kilometre

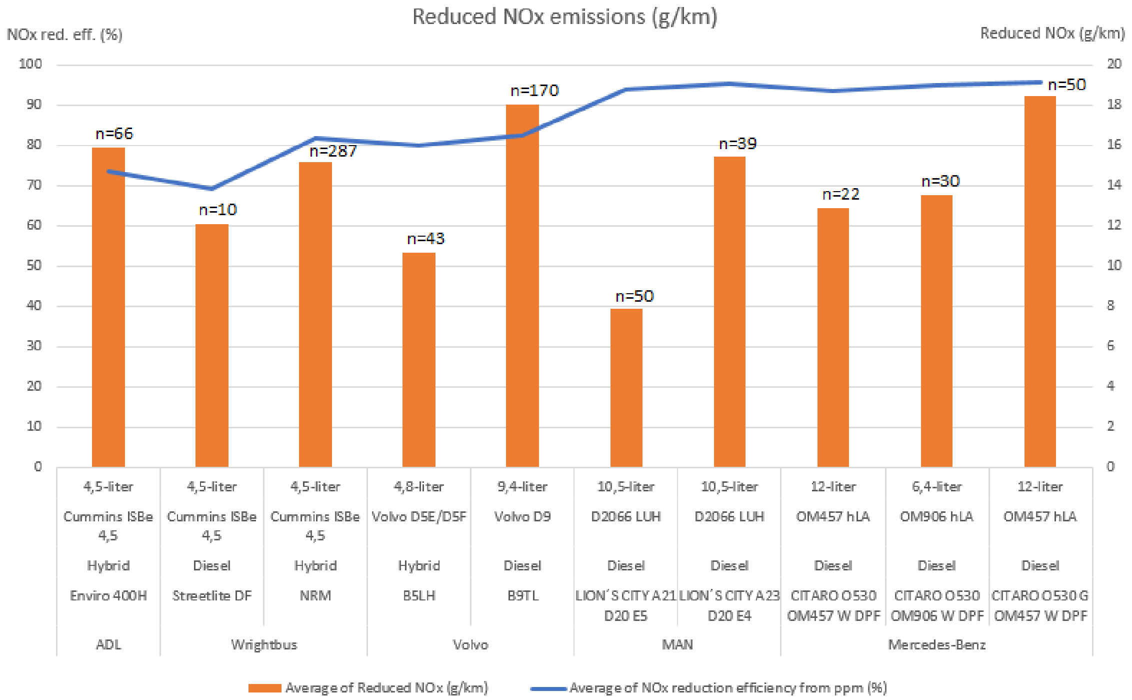


Figure 5-12: Reduced NOx emissions per kilometre

5.1.7 The influence of driving conditions

In addition to reduction efficiency, grams per kilometre emissions are influenced by engine size and driving conditions, especially speed. The average driving speed and emissions per kilometre within these vehicles can be seen in Figure 5-13.

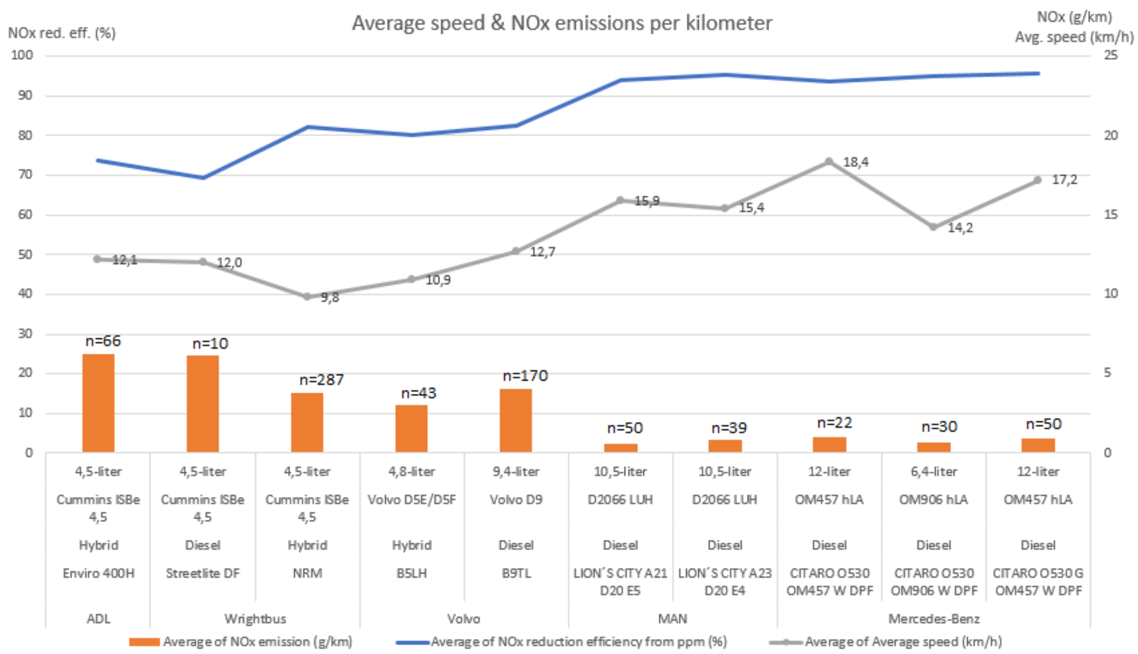


Figure 5-13: Average driving speeds and NOx emissions

By looking at the picture, it can be seen that vehicles with the smallest NO_x emissions have slightly higher average speed than vehicles with the largest emissions. To illustrate the effect of driving speed to emissions, individual vehicle's emissions relation to driving speed was studied.

When investigating the relation between single vehicles' driving speed and emissions, filtering from date was removed. This enabled the selection of a vehicle with the most data for comparison. To see the influence of driving speed to NO_x emissions, daily values were sorted ascending by driving speed. Figures 5-14 and 5-16 visualise the relation between these measurements for ADL's Enviro 400H and Mercedes' Citaro O530 G. The selected examples of single vehicles have been chosen to match the single vehicle's average EAT system efficiency to the average efficiency of the group in question as close as possible.

Figure 5-14 shows that operating the vehicle in higher speeds reduces the NO_x emissions per kilometre. In Mercedes, similar decrease of the emitted NO_x per kilometre cannot be noticed as the speed increases. The overall NO_x reduction efficiency in the investigated Citaro is about 95% while in the Enviro 400H it is about 75%. Also, must be noted that the operating speeds in Mercedes remain notably higher. In heavily congested cities, buses' average driving speeds stay very low and the emissions per kilometre are higher, therefore it is important that the EAT systems operate efficiently in this kind of conditions.

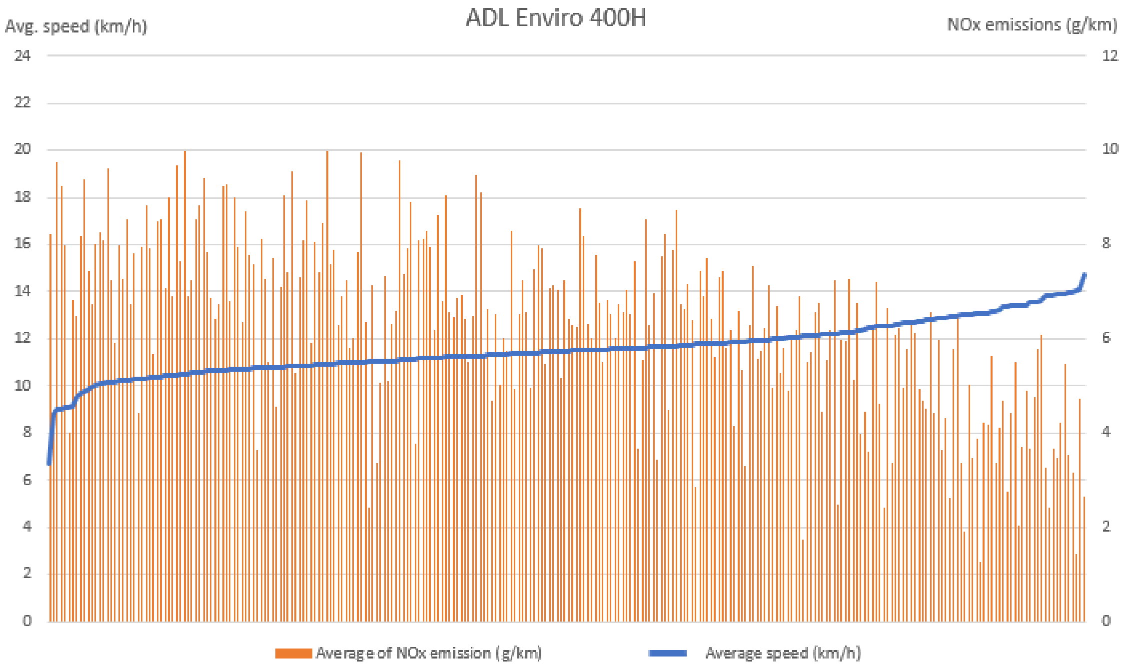


Figure 5-14: ADL Enviro 400H NOx emissions (g/km) related to speed

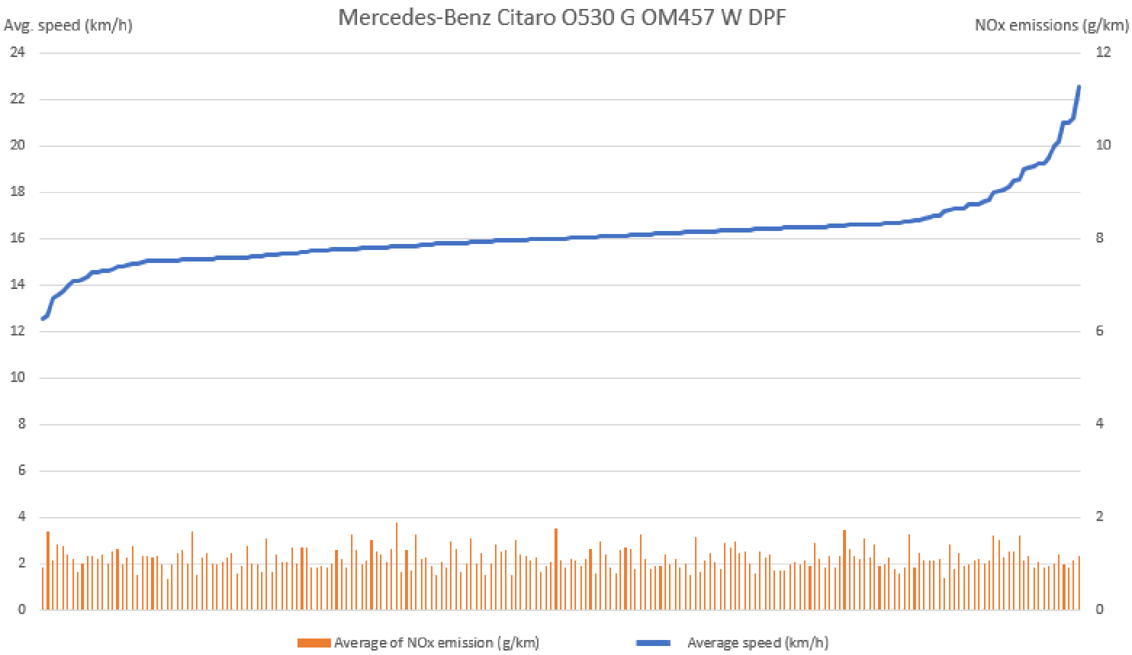


Figure 5-15: MB Citaro O530 G (articulated) NOx emissions (g/km) related to speed

From all the buses, Wrightbus New Routemasters have the lowest average speed because they operate in congested areas near the city centre. Example of Wrightbus NRM (Figure 5-16) shows that the average operating speeds mainly stay under 14 km/h while Mercedes Citaro O530 G's average speeds (Figure 5-16) remain above this and may reach up to 22 km/h.

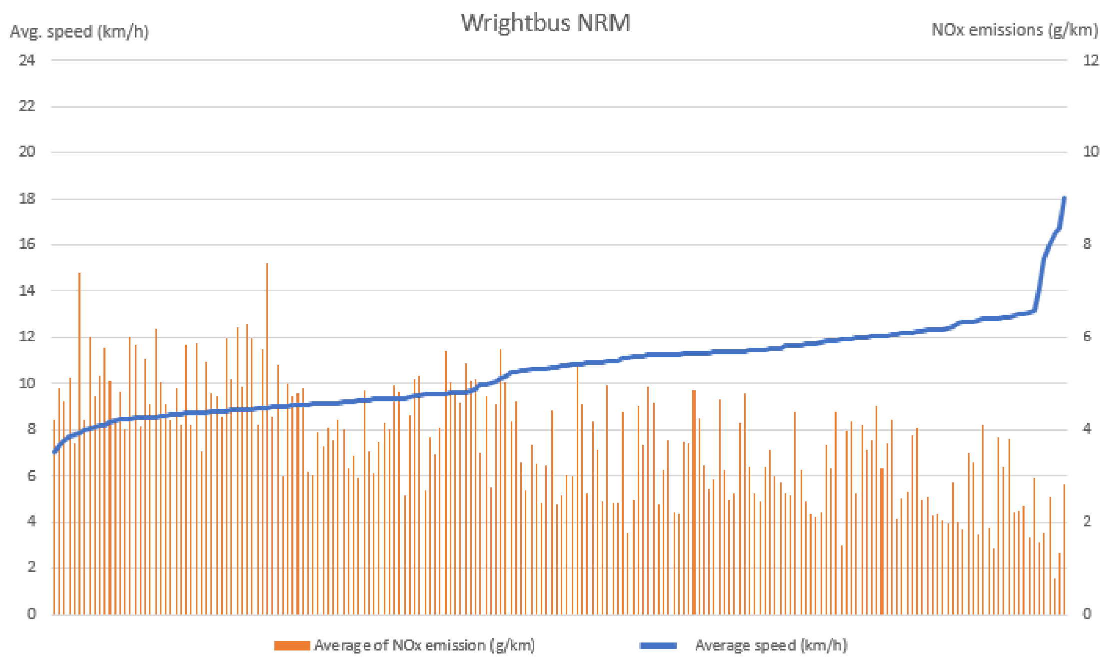


Figure 5-16: Wrightbus NRM NOx emissions (g/km) related to speed

As mentioned earlier in this document, exhaust temperature is a significant factor for operation of the aftertreatment system. The relation between operating speed and exhaust temperature was investigated in the same buses than the examples above. As the average speed increases a slightly rising trend is noticeable in temperatures within Enviro 400H and New Routemaster (Figures 5-17 and 5-18).

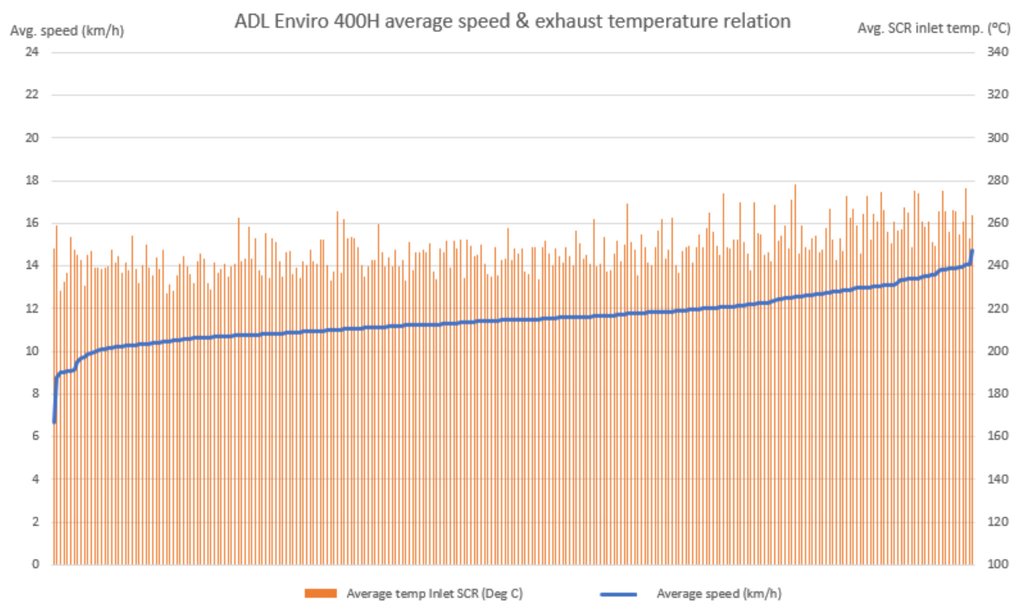


Figure 5-17: ADL Enviro 400H relation between driving speeds and exhaust temperatures

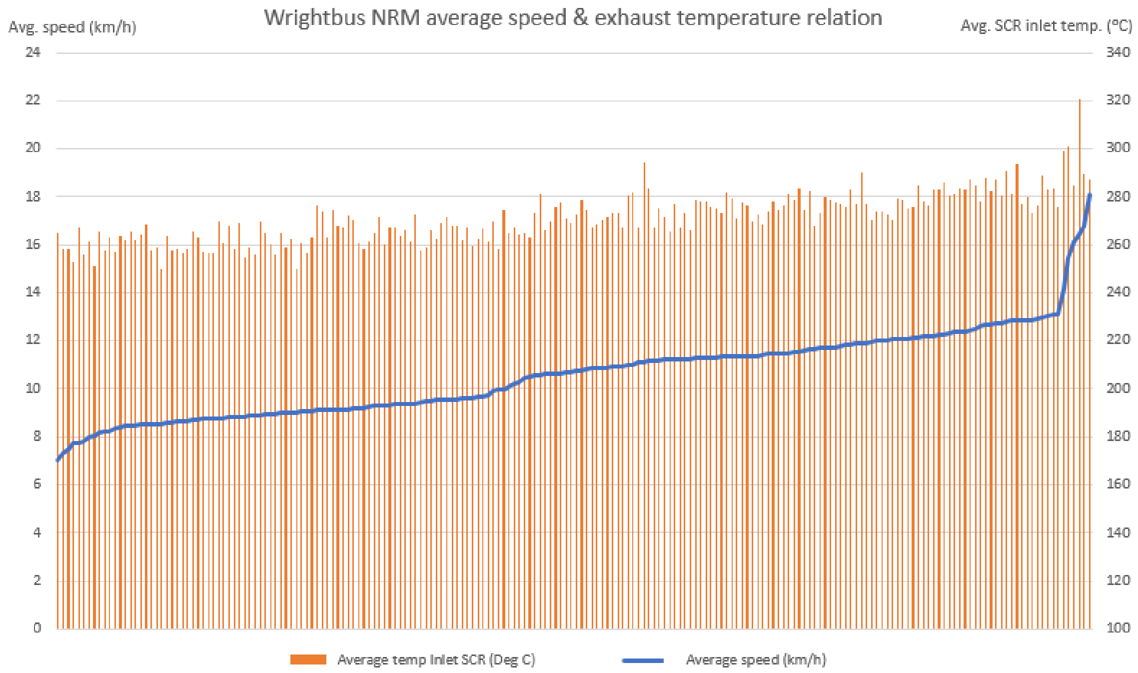


Figure 5-18: Wrightbus NRM relation between driving speeds and exhaust temperatures

In addition to articulated Citaro, average speed and temperatures were also studied in a solo Citaro which is equipped with the same OM457 engine. Figure 5-19 represents the behaviour of exhaust temperatures with increasing speed for articulated Citaro O530 G and Figure 5-20 for a solo bus Citaro O530.

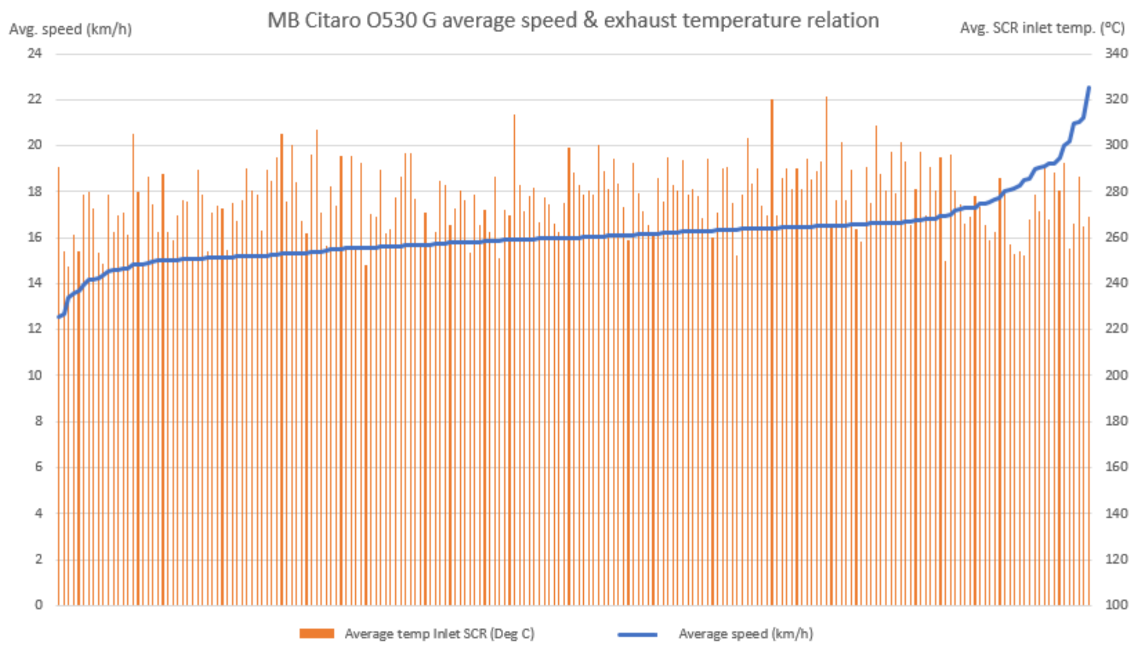


Figure 5-19: MB Citaro O530 G Average operating speeds & exhaust temperatures

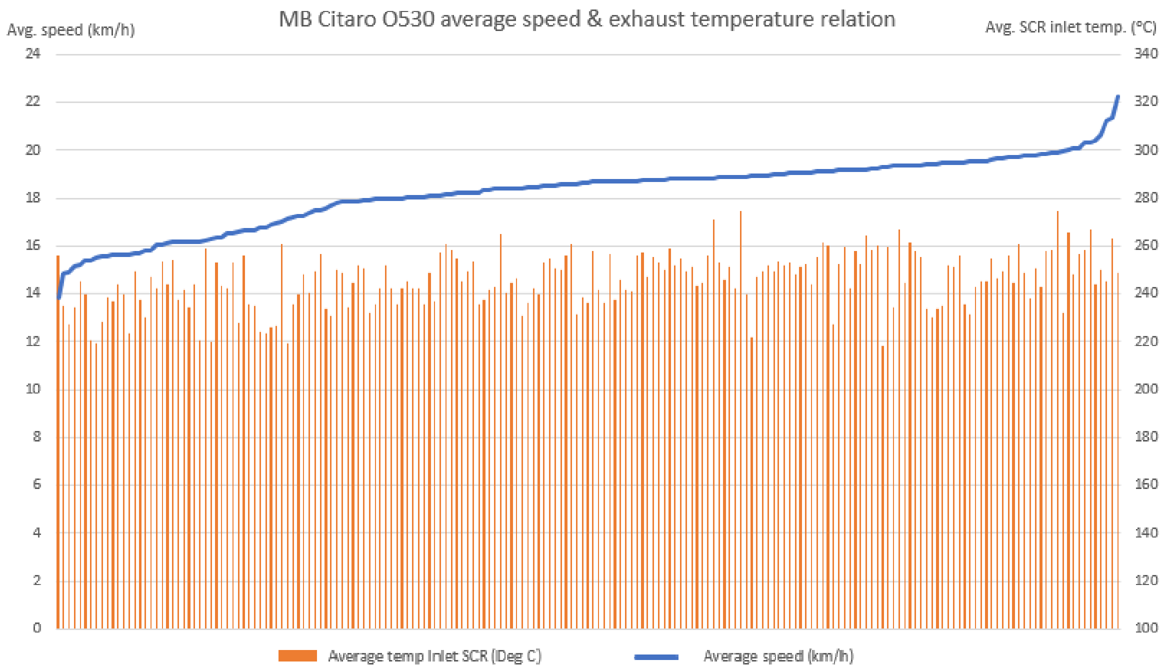


Figure 5-20: MB Citaro O530 average operating speeds & exhaust temperatures.

Exhaust temperatures and ambient temperatures were observed in monthly averages within different bus types. A noticeable trend shows that exhaust temperatures remain higher during the summertime when the ambient temperature is also higher. This phenomenon was more notable in diesel-powered buses than in hybrid buses. Figure 5-21 shows the monthly average ambient temperatures and variation of exhaust temperatures for three different hybrid buses operating in London.

The Figure 5-21 shows that the ambient temperature variation has no significant effect in NRM's exhaust temperatures. There is not clear effect on Enviro 400H's exhaust temperatures either but in B5LH temperatures are slightly increasing towards the warmest month.

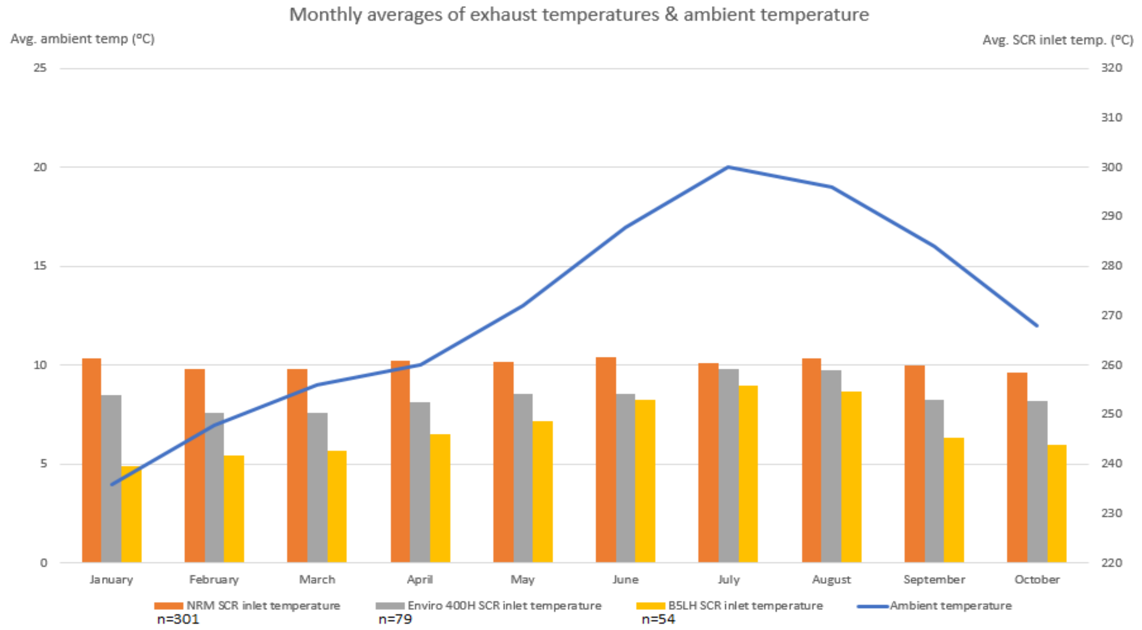


Figure 5-21: Exhaust temperature comparison between NRM, Enviro 400H & B5LH

A similar comparison was made between three diesel-powered double decker buses that operate in London; Volvo B9TL, ADL Enviro 400 and VDL DB300. Volvo is using Volvo's 9,4-liter diesel engine and E400 and DB300 are both equipped with Cummins' ISBe 6,7-litre engine. Monthly exhaust temperature variations between these models can be seen in Figure 5-22.

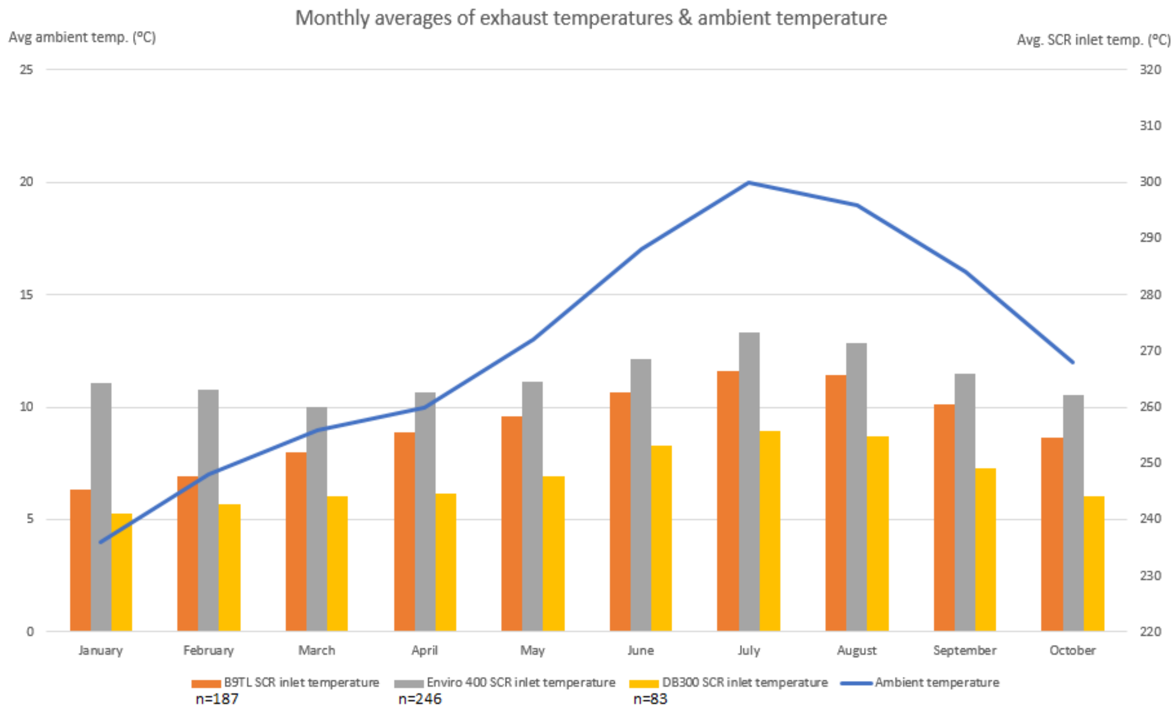


Figure 5-22: Exhaust temperature comparison between B9TL, Enviro 400 & DB300

The graph above shows that the exhaust temperatures remain higher in each bus during the warmest months. It can be also noted that temperature variations are slightly larger in B9TL than in Enviro 400 or DB300.

The effect of ambient temperature was also studied between two types of solo buses that operate in London. Mercedes Citaro is equipped with six-cylinder 6,4-litre OM609 engine and the slightly smaller ADL Enviro 200 is powered by four-cylinder 4,5-litre ISBe engine. Differences in the exhaust temperatures between these solo buses are shown in Figure 5-23. This figure reveals that even the exhaust temperatures behave quite similar, Mercedes' temperatures remain much higher than ADL's through the reviewed period.

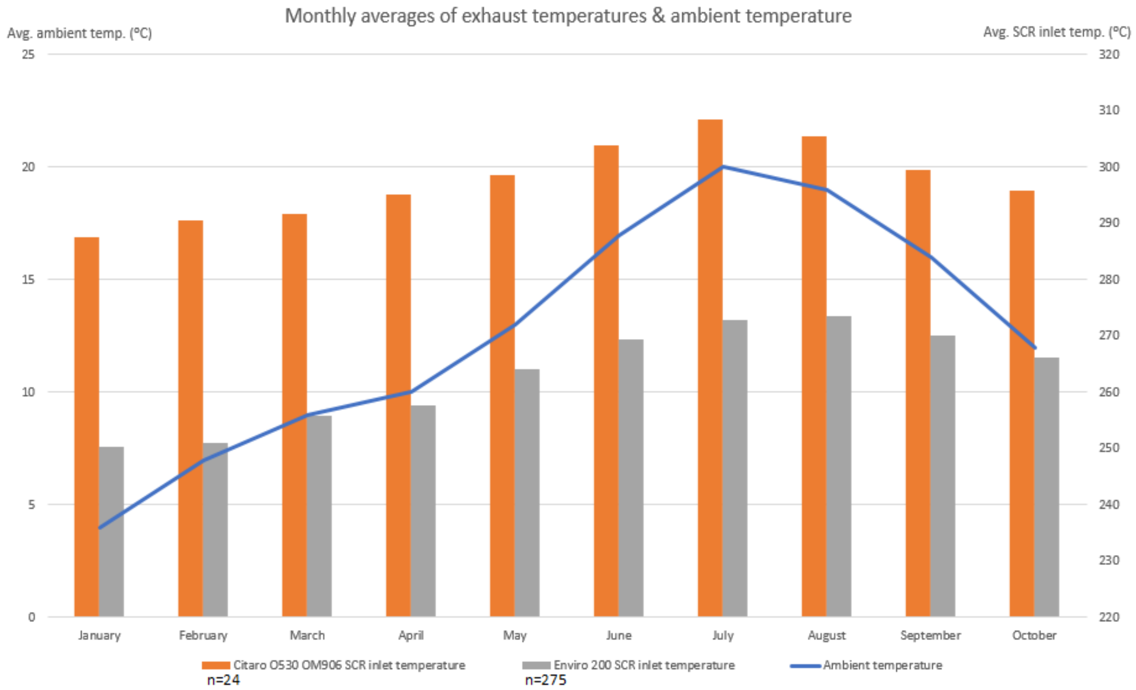


Figure 5-23: Exhaust temperature comparison between Citaro O530 OM906 & Enviro 200

Figure 5-24 represents the exhaust temperature behaviour within four bus types operating in Aachen, Germany.

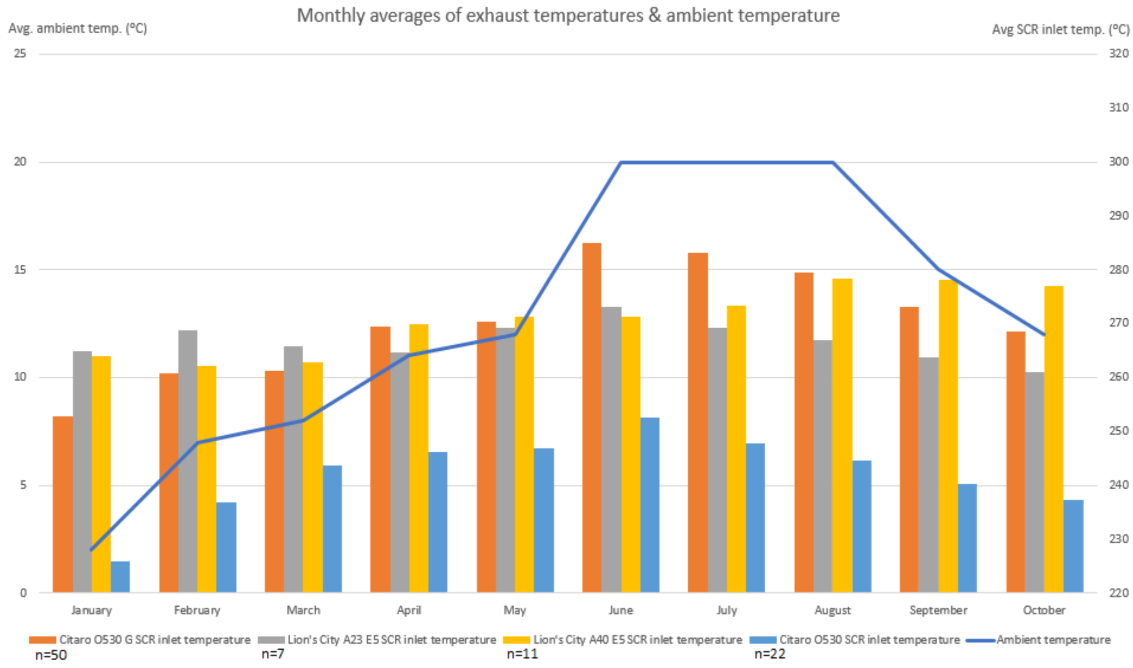


Figure 5-24: Exhaust temperature comparison between Citaro O530 G, O530, Lion's City A23 & A40

The EAT systems in all these bus models are operating in high, over 90% NO_x reduction efficiency. Both Mercedes' buses, Citaro O530 and O530 G are powered by 12-liter OM457 diesel engine while Lion's City A23 and A40 are both using smaller MAN's 10.5-liter D2066 LUH engine. By looking at the picture, it can be seen that exhaust temperatures in Mercedes' buses are correlating with ambient temperatures more than temperatures in MAN's buses. Also, it should be noted that temperatures in solo Citaros are staying notably lower than in articulated Citaro O530 G.

5.1.8 Exhaust Temperatures & Reduction Efficiency

The behaviour of the EAT system when exhaust gas temperatures are increasing were compared between various bus models. The following graphics include the daily values for all the buses that had recorded data in period of 10 months from January to October. The n in the figure states the count of buses and the light blue on the background indicates the daily values of NO_x reduction efficiency with increasing average SCR temperatures, which is presented with the orange line. The dark blue trendline has been included in order to ease the interpretation. When comparing Enviro 400H and NRM, graphics reveal that exhaust temperatures remain slightly higher in NRM and the average reduction efficiency is about 80% when the average temperature is 250, while in the 400H the efficiency reaches 70% in the same temperature. The relation between NO_x reduction efficiency and exhaust temperatures between these models are shown in Figures 5-25 and 5-26.

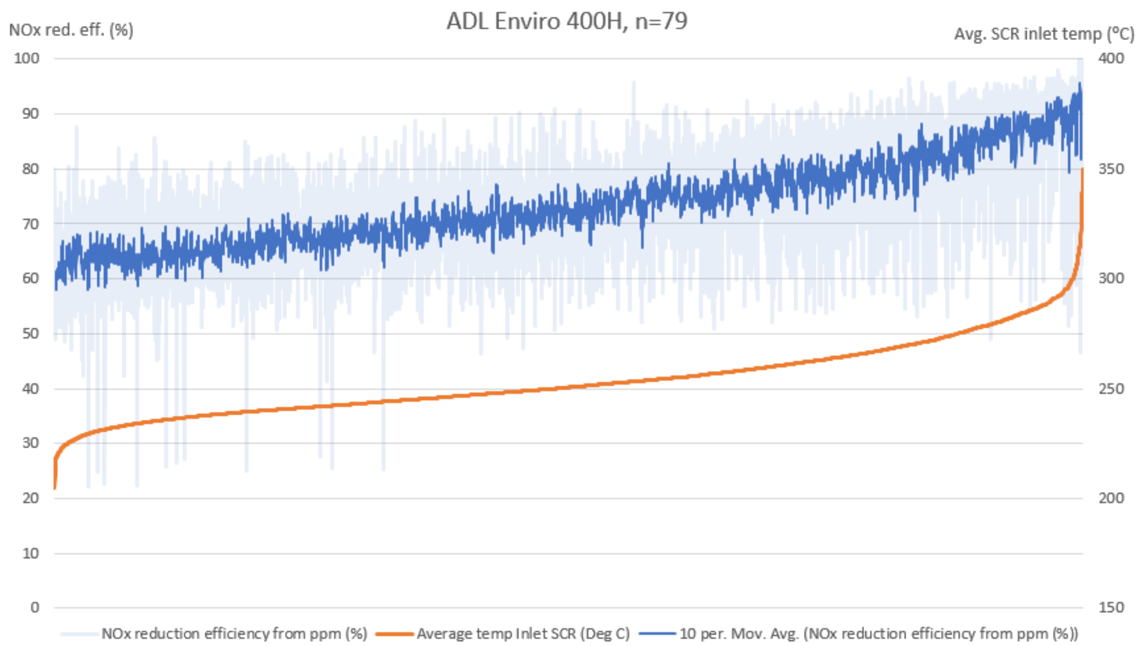


Figure 5-25: Enviro 400H NOx reduction efficiency related to exhaust temperature

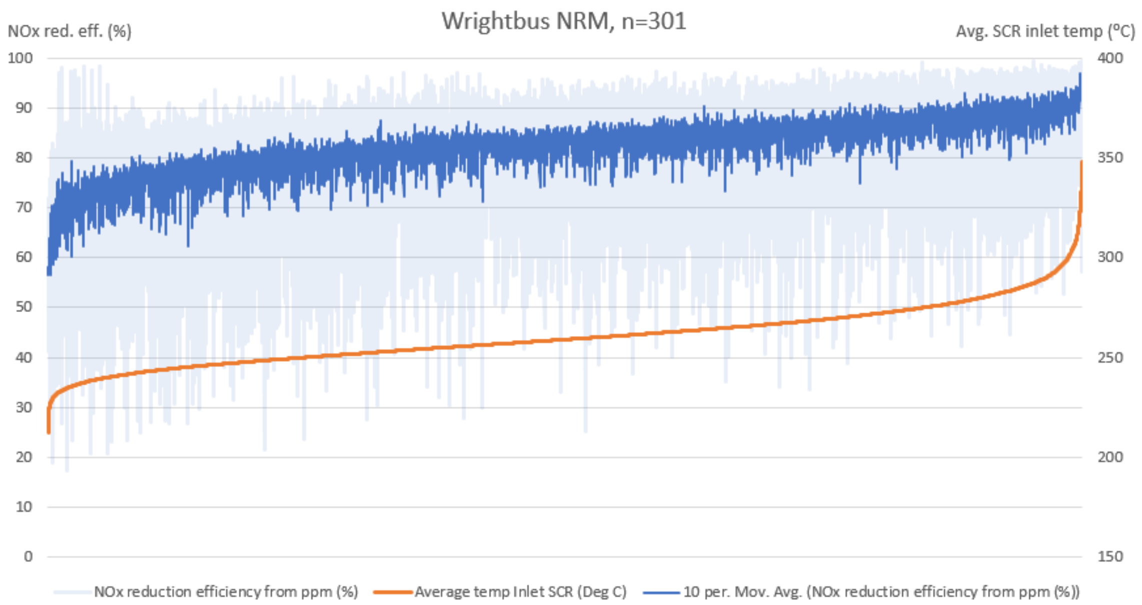


Figure 5-26: Wrightbus NRM NOx reduction efficiency related to exhaust temperature

In comparison ADL's Enviro 200 is also equipped with the same Cummins ISBe engine but without hybrid technology. The behaviour of the EAT system is similar with Enviro 400H when temperatures increase, but the overall efficiency remains higher due to slightly higher exhaust temperatures. Enviro 200's EAT system efficiency related to exhaust gas temperatures is presented in Figure 5-27.

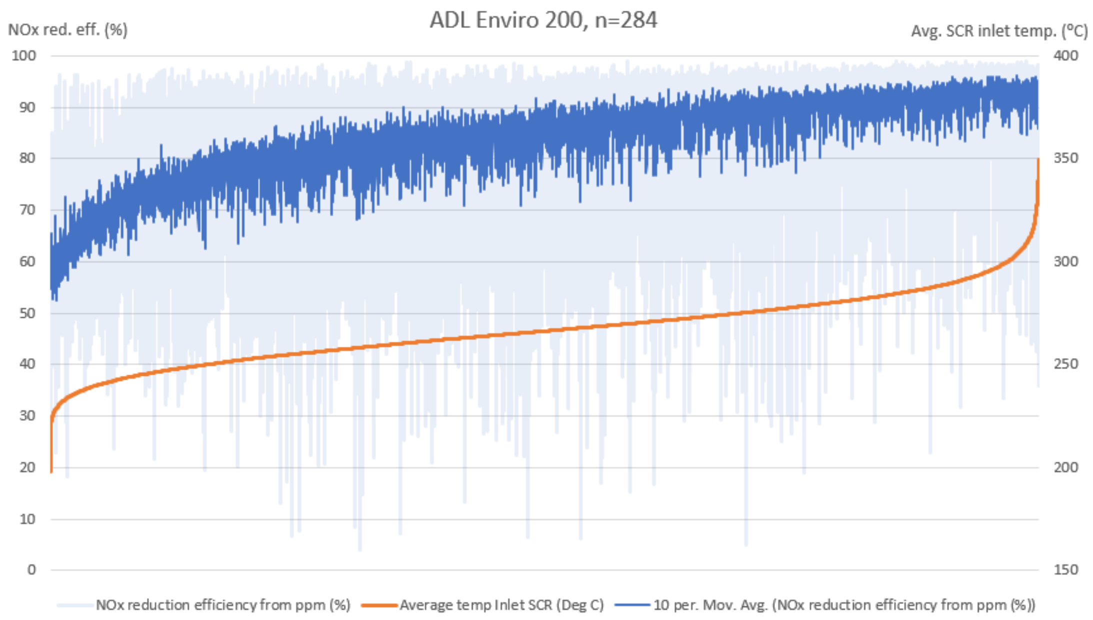


Figure 5-27: Enviro 200 NOx reduction efficiency related to exhaust temperature

When these models are compared with Mercedes Citaro O530 G or MAN Lion's City A21 can be seen that the EAT system efficiency in both these models remains constantly close to 90% or above and dramatic decreases in NOx reduction does not occur even at low temperatures such as 230 ^{o}C. The EAT system efficiencies for Mercedes Citaro O530 G and MAN Lion's City A21 are presented in Figures 5-28 and 5-29.

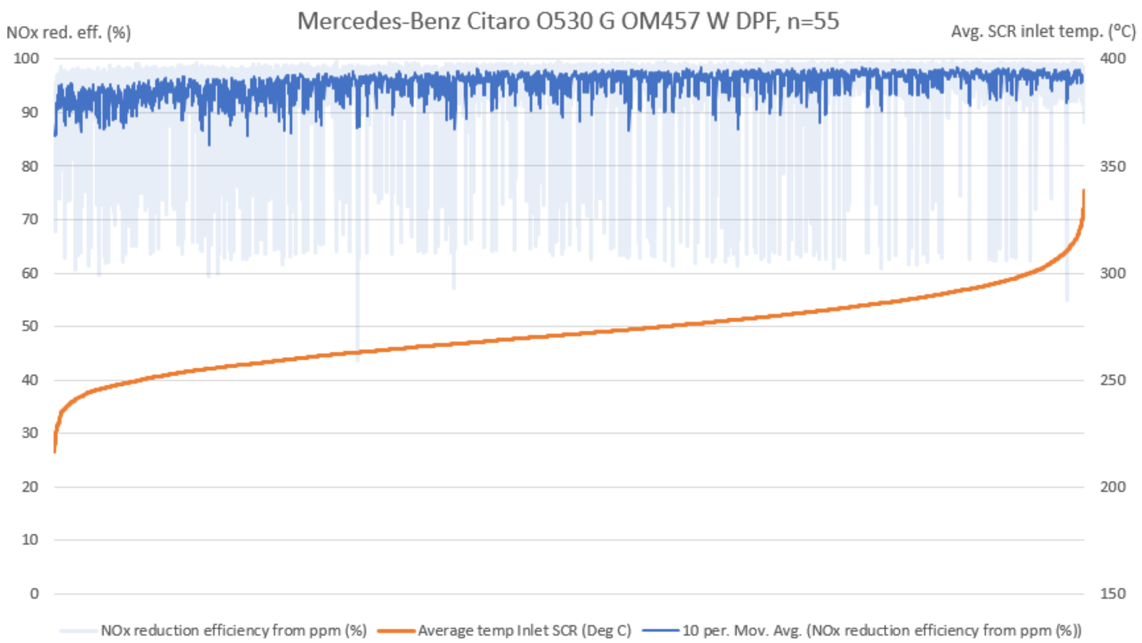


Figure 5-28: Citaro O530 G NOx reduction efficiency related to exhaust temperature

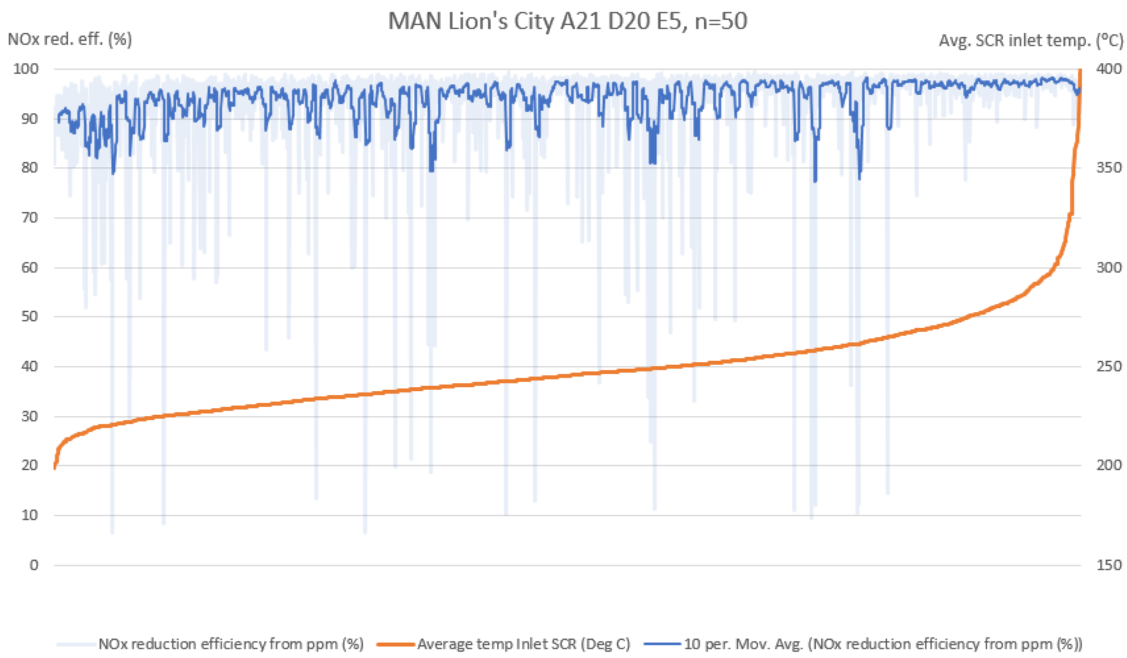


Figure 5-29: Lion's City A21 NOx reduction efficiency related to exhaust temperature

5.1.9 Temperature Relation to NOx Reduction & Emissions

The study of the exhaust temperatures and the efficiency of the EAT system was carried out on various bus models by including recorded values from multiple buses to one graph. Few examples reveal, how big of an impact the SCR temperatures have on the NOx reduction efficiency when values were sorted ascending by average exhaust temperatures. Figures 5-26…29 represent the change of the reduction efficiency with increasing SCR temperatures within various bus types. By looking at the graph for Enviro 400H (Figure 5-25) can be seen that 50 ^{0}C increment in the average SCR temperatures from 250 to 300 increases the average reduction efficiency from 70% to 90%.

When studying the emissions and the reduction efficiency it can be noted that the variation in EAT system efficiency in typical Enviro 400H is very large. Increasing the reduction efficiency from 65% to 95% for Enviro 400H means drop in NO_x emissions from 10 g/km to below 2 g/km. If the daily average NO_x emissions could be kept in 2 g/km instead of 10 g/km would that mean 1.2 kg more of reduced NO_x on a daily operation if the driven distance would be 150km. The relation between NO_x reduction efficiency and emissions in typical Enviro 400H can be seen on Figure 5-30.

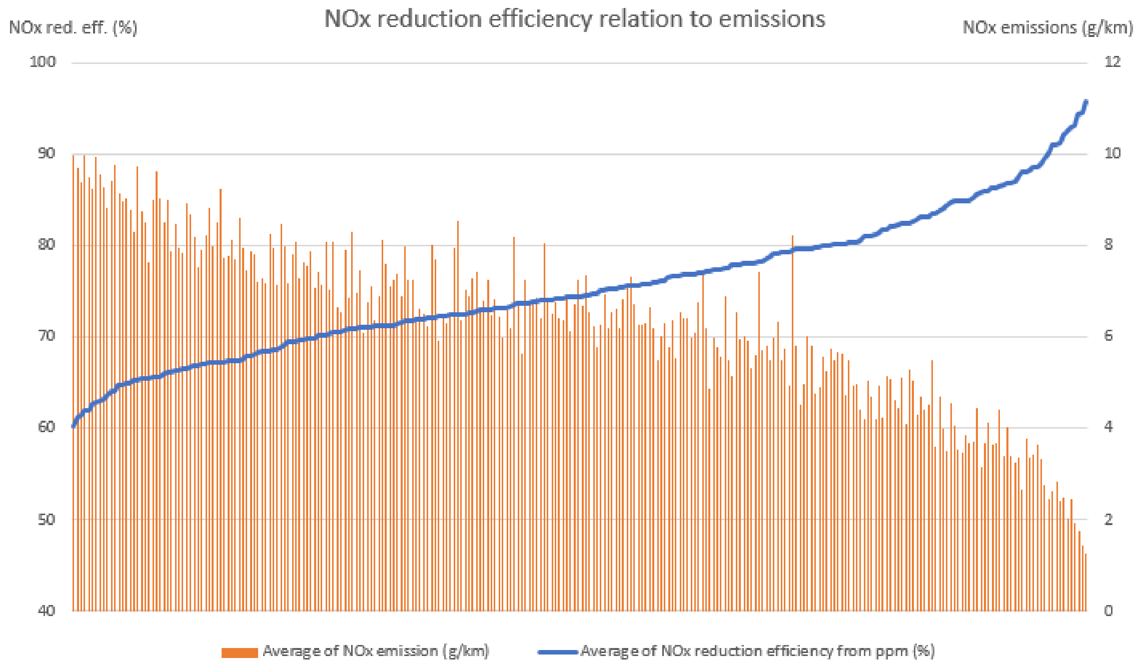


Figure 5-30: Impact of reduction efficiency to emissions in typical Enviro 400H

When viewing an average Mercedes-Benz Citaro O530 G when the reduction efficiency readings have been sorted ascending, it can be noted that the line follows closely the trendline that has been presented in Figure 5-28. Figure 5-31 represents an example of typical Citaro O530 G and reveals that constant high efficiency of the EAT system keeps the emissions low under 2 g/km.

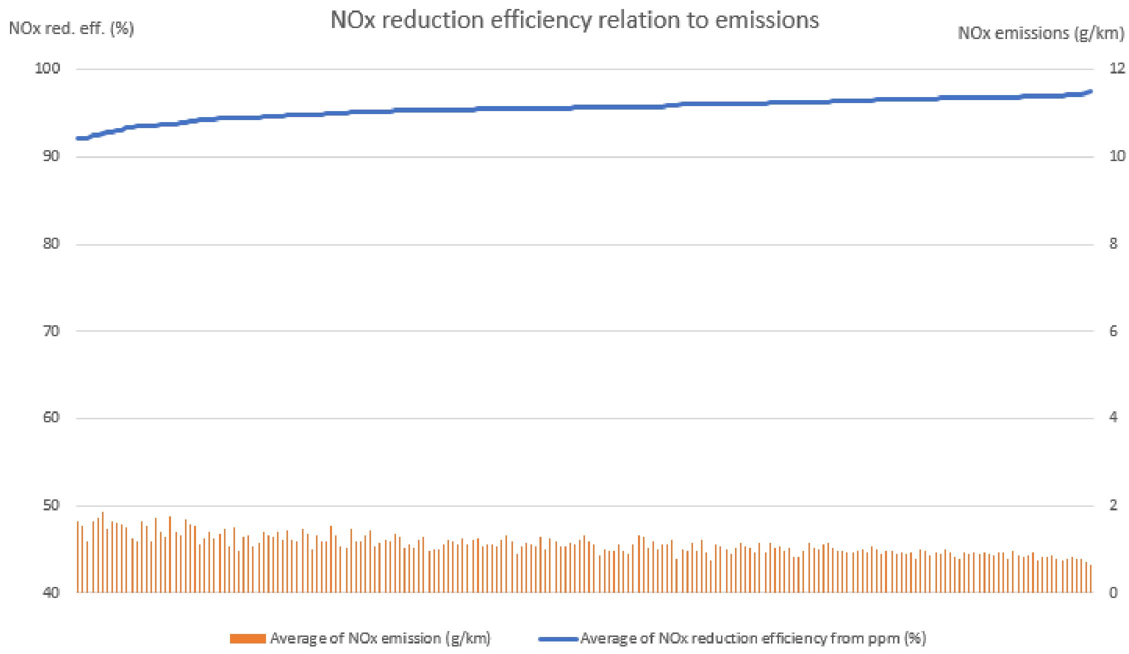


Figure 5-31: Impact of reduction efficiency on emissions in typical Citaro O530 G

In addition to the poor maintenance, tampering the vehicle's EAT system has a similar effect. Tampering means removing, disconnecting, altering, bypassing or rendering ineffective any pollution control equipment installed in a motor vehicle. Tampering with a vehicle emissions control system is illegal and can negatively affect the vehicle performance and contribute to air pollution. The example in Figure 5-32 represents the effect of a tampered vehicle.

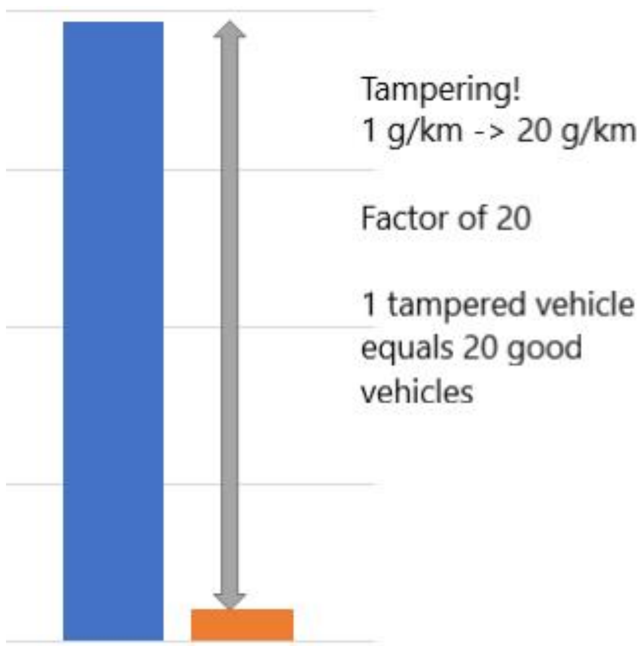


Figure 5-32: Tampering effect

As the figure shows, emissions from one faulty or tampered vehicle can equal 20 good vehicles. In the worst case this factor can be even larger, and therefore it is necessary to eliminate these vehicles from traffic and polluting the environment.

5.1.10 Discussion

The research data included information on over 1500 buses which have been equipped with Proventia's retrofit EAT system. The goal of this study was to find various factors that affect the operation of the EAT system and to get a clear picture of which vehicles the system is operating with great efficiency or if there are problems with certain models.

Retrofitting is efficient way to reduce NO_x emissions quickly in highly congested cities with lots of buses. Crowded cities also create very challenging operation conditions, and therefore it is important that the operators ensure the proper maintenance of the buses and do not release vehicles with faulty EAT system to traffic. Although, there are multiple factors that must be considered in retrofitting buses, by interpreting the presented data, it is fair to say that the retrofitted EAT system allows significant reduction in the NO_x emissions within the studied vehicle fleet. Also, the reduction efficiencies remain high when no defects occur.

5.2 Retrofit projects overview and analysis

Retrofit projects in this overview are classified according to market area and vehicle type.

5.2.1 Germany

In Germany retrofit projects are controlled by KBA (Kraftfahrt Bundesamt, www.kba.de) and there is type approval process for retrofit systems to be allowed to enter market. Retrofits technical requirements are different for different vehicle classes and reflecting different usage profiles. All vehicle classes are tested as vehicle tests using PEMS measurement. PEMS measurement may not possibly measure all require so called nonregulated emissions (such as NH_3, N_2O etc.), and in that case supplier has to prove in another way that retrofit system complies with emissions of those components. As NOx reduction efficiency is criteria, measurement is to be done using two PEMS systems (before and after emission control system) or running test procedure two times.

City buses are measured using real bus line with PEMS. It is required that system has minimum of 85% NOx reduction at ambient temperature of -7°C. This NOx reduction efficiency is measured from engine out emissions, not after possible earlier SCR in original layout. Vehicle speed is known to have impact on emissions as g/km and there are 5 speed steps with each highest emission limit. On top of NOx limits, NH_3 control is required, OBD, proof of secondary emissions and CO_2 may not increase more than 6% compared to baseline. Retrofit system scaling is possible within same base emission class (Euro III, IV, V) and if and base technology (EGR/SCR/DPF). Most simple scaling is if from same emission class is tested solo bus with small and large engine, and articulated bus. This covers basically all bus variant in the market. Lifetime requirement is 200.000km/4 years.

Municipal vehicles, such as garbage trucks, are having retrofit regulation. Testing has minimum reduction efficiency over PEMS test (85%), but also minimum NOx reduction rate at temperature windows. Example if lowest temperature window is at 160°C, NOx reduction efficiency needs to be 60%. This is to reflect low speed and therefore low exhaust gas temperature during urban waste collection operation. It is possible that certain vehicles are operating outside of their normal operation mode in these test cycles. Focus on regulation is at low speed operations and as such easy to justify. Lifetime requirement is 200.000km or 4 years.

Table 5.5: City bus retrofit emission limits for Germany

Speed class [km/h]	Speed range [km/h]	Limit [NOx g/km]
10	7.5-12.5	7.5
15	>12.5-17.5	5
20	>17.5-22.5	4
25	>22.5-27.5	3
30	>27.5-32.5	2.5

Light commercial vehicles (N_1, 2.8-3.5tn) are following similar limits as municipal vehicles and minimum of 85% NOx reduction at PEMS test. Approval lists vehicle model variants included in type approval and in general scaling to lower power is possible, but scaling is more limited to variable engine sizes.

Passenger cars are also tested as PEMS test and limit is NOx 270mg/km at PEMS test. PEMS route includes 1/3 of urban, 1/3 of rural and 1/3 or highway driving. Highest speed at highway part is up to 145km/h. Same limitations on secondary emissions and CO_2 increase (max +6%) apply also to passenger cars. Lifetime requirement is 100.000km or 5 years is applicable for light commercial vehicles and passenger cars.

5.2.2 United Kingdom

Buses, coaches and trucks are within retrofit regulations and process is coordinated by Energy Saving Trust (EST), unless buses are operated in London, then Transport for London (TfL) is coordinator. Retrofit in London has long history and DPF / SCR retrofits have been in place for several years. Current latest regulation if for buses originally Euro IV and V. Test procedure includes testing of actual vehicles on chassis dyno as well certain period of field testing after passing emission limits at test laboratory. Buses are tested on LUB cycle, or Millbrook test cycle in London and couches on LUC cycle. NOx emissions should be less than 0.5 g/km and NO_2 less than 0.1g/km. Several details include secondary emission measurements and also particle number limit. Heavy duty trucks and refuse collection vehicles (garbage trucks) have their own test cycles. Garbage trucks have lower ambient temperature during test (+10°C) as well lifting arm operation and waste compaction operations during testing. Testing includes periods for dense urban collection, suburban collection, as well transfer operation. Design lifetime of retrofit system is 7 years.

Emission monitoring telemetry is mandatory in all buses in London. Due to variable driving conditions and sometimes heavy congestions, average driving speeds are significantly lower than in test cycles. Lower speed lowers exhaust gas temperatures and further increase emissions (as g/km).

Table 5.6: City bus retrofit (primary) emission limits TfL

Emissions	Limits
NO_x	0.5 g/km
NO_2	0.1 g/km
PM	0.01 g/km
PN	6.0×10^{11} /km

Table 5.7: City bus retrofit (secondary) emission limits TfL

- **Secondary Emissions Limits**
- ***Nitrous Oxide (N_2O) and Methane (CH_4)***
- The CO_2eq must not constitute more than 5 % of the total CO_2 emissions recorded during the test. The following equation will be used for CO_2eq
- CO2eq = 298 x N2O + 25 x CH_4
- ***Ammonia (NH_3)***
- Ammonia emissions are limited to 10 parts per million (mean)
- ***Carbon Dioxide (CO_2)***
- CO_2 emissions shall not be adversely affected by more than 1% (within test repeatability) by the fitment of NOx Abatement Equipment

source: https://energysavingtrust.org.uk/sites/default/files/CAZ%20CVRC%20Chassis%20DynamometerTest%20Procedures%20for%20Low%20Emission%20Adaptations%20v11.0%2023Sep2019.pdf

5.2.3 Other Countries

UN ECE R132 is retrofit regulation covering on-road and non-road vehicles. Target is to have similar process as new homologation tests for engines. This requirement is technologically sound, but commercially heavy. Retrofit market is fragmented and market potential is not always very clear. Also emission tests are made with engines at dyno, which standardizes conditions. On the other hand, during diesel-gate scandal it was widely discussed that real drive emissions are what counts. Possible drivetrain features can affect emission performance heavily, see also previous Chapter 5.1..

There have been local retrofit regulations to cover range of vehicle, on-road or non-road, in several countries and cities. As a smallest scale those have been single tendering rounds with vehicles of some pieces. And as larger scale those have covered hundreds of vehicles operating in certain limited area. Such retrofit projects have been in at least Netherlands, Spain, Italy, Nordic Countries and under VERT – organisation.

5.3 Analysis of potentials of different applications for retrofits

Obviously retrofitting on-road vehicles operating in dense population areas are most attractive applications for retrofitting. Vehicle population / type is high enough to justify test and design cost for each variant. And emissions are reduced directly from street corridors where exposure is highest.

Retrofitting of passenger cars with SCR is possible and there are approvals for those. Fragmented market and business to consumer -style business sets different limitations. It is difficult to justify retrofitting only by emission reductions, also other tools are needed. Those tools could include incentives, driving restrictions etc.

For non-road applications, usage and installation varies a lot. This is setting higher cost for design and testing for approval. Retrofitting same engine but installed in another application might require retesting and following possible in-use tests. This might raise the development and certification costs make retrofitting non-feasible. If installed population is only few examples, statistical analysis of emission benefits is difficult.

In generally, retrofitting should reduce emissions (converter into financial terms), higher than installation and operation costs over lifetime. Cost/benefit of reduce NOx gram varies geographically and it is not possible to set just one value. If certain vehicles are creating locally high emission spot - example one bus line polluting certain bus stop at street corridor – then value for NOx from those buses is different than other bus operating in other area where there is no specific emission problem. Residual value of vehicle and lifetime cost of retrofit system should be in balance.

5.4 Methodologies to verify the durability of the retrofits

In German regulations retrofits are verified under type approval and those are controlled by KBA. KBA has right to test vehicles and make in-service conformity tests to retrofit systems. This includes partial testing, such as function of certain OBD part or full testing of the system in including PEMS testing. Manufacturers of emission control devices are requested to do annual in-service conformity tests for duration of four years and report those to KBA.

In London all retrofitted buses (which are to reach latest Euro VI emission level) are equipped with some sort of remote telemetry to monitor emission performance of the buses. TfL has set general guidelines how emission monitoring system should work and what parameters are to be reported. By having common rules and principles, different calculation methods and possible unwanted filtrations are minimized.

Durability monitoring should be continuous and transparent. In chapter 5.1., it was demonstrated that one single non-working after-treatment system is emitting 20 times more NOx emission than properly functioning. For this reason, fixing faults as early as possible is great benefit for environment.

PEMS measurement of selected vehicles periodically gives reference emissions. Telemetry gives indication of emissions, but sensor drifting, and other inaccuracies are left out. For sorting out worst emitters, online telemetry is the fastest tool.

6 Conclusions and implications

This deliverable combines literature review of three main themes: detecting high-emitting vehicles with periodic inspections and tests, probing and gauging the performance of EAT systems by on-board diagnostics (OBD), and assessing the potential of lowering the harmful emissions of vehicles and NRMM by retrofitted EAT devices.

While comparing the characteristics of the inspection and maintenance (I/M) programmes in US, and the procedural progress of PTI, associated with the upholding of the roadworthiness of motor vehicles in Europe, an interesting fact was revealed. Namely, in US the preservation of air quality has always had the highest rank regarding the inspection of the condition and performance of motor vehicles, while in Europe, safety-related aspects have always been the most important features of such an inspection. This is clearly reflected in the fact that in US there are numerous states and densely-populated urbanizations, where emissions-related I/M programmes are mandatory for safeguarding low exhaust emissions. However, there is no periodic inspection (PTI) that should take care for the safety-related issues. In contrast, the European directives relating to the contents and procedures of PTI are clearly emphasising safety aspects, like the condition of brakes and other chassis items, over probing the performance of the EAT system. Furthermore, knowing how adversely motor vehicles have for several decades attributed to the bad ambient air quality in US, this is no surprise.

The more detailed review of the US I/M programmes showed, how there has been almost constant evolution of the procedures used in probing the level of in-use emissions, as well as an equally steady evolvement of the performance and complexity of the EAT systems. However, similar progress has not taken place in Europe, as the emissions checks included in present version of the prescription for PTI does not include any relevant means to gauge emissions of NOx and particulates (PM, PN) that are the primary contributors and precursors for low ambient air quality in many European cities. Furthermore, it was discovered that this issue is not technical but more of a legislative case, because according to the literature, several large scale studies have developed and presented procedures applicable to NOx and PM/PN that could be implemented as parts of the PTI regulations, but the EC legislators has failed to do so by today.

Furthermore, despite the apparent pre-eminence of the US programmes, many of the cost-benefit analysis reviewed criticise the system about high costs vs. achieved improvements in air quality. But, it is only fair to say that if there has not been I/M programmes, the air quality in most of the metropolis of United States would be simply intolerable. Equally, the more lenient approach that EU has taken regarding checking the levels of exhaust emissions, in association with the periodic technical inspections now mandatory across Europe, is shown to have contributed to the worsening of ambient air quality in many densely-populated and heavily-trafficked cities.

However, partially this is situation due to fraudulent attitude of many European car manufacturers and the resulting wide-spread incompliance of the EAT systems fitted in EURO 5 diesel-powered cars. But, partially it is also due to the fact that even if several good quality attempts has been made to enhance the scope and effectiveness of the PTI-procedures regarding the most important contributors, NOx and particulate emissions, the legislators have not been able to implement those in related directives. Instead, the response to the epidemic exceedance of air quality guidelines observed across Europe has been the attempts to restrict traffic. As by law, the local authorities are in charge of the air quality and should react if exceeds in the air quality limit values happen repeatedly. Should this happen, the authorities need to create a plan, how to harness this adverse phenomenon. Usually, they cannot do more than place restrictions to the traffic, and create zoning systems, where the type approval emissions level of the vehicles is used as a distinguishing factor and form the basis for approving or denying access. Today, these “low emissions zones” are quite widespread across European cities.

As a further option for identifying high emitters, Remote Sensing Technologies were also studied. Remote sensing device (RSD) measures an instantaneous emission rate of individual vehicles as they pass by the instrument location. It is not an exact measurement, and the results are rather expressed as emissions in g per g of fuel burned. As such, it can give valuable information for air quality monitoring and development of emissions models. It can also be used for in-use surveillance, to determine the average emission rates under real-driving conditions and assess the long-term durability of EAT systems.

First introduced already in late 1980s, the technology has ever since taken substantial leaps, and is now commercialised by several suppliers. Today, a fully functional remote sensing device (RSD) set-up has a pollutant analyser and a camera device for linking the measured values to a license plate, and in some case even with additional vehicle data retrieved simultaneously on-line OTA from a registration database. Furthermore, information of the acceleration of the vehicle during exhaust plume scanning is provided. The latest models add nitrogen dioxide (NO_2) to pollutants detected by the earlier device’s nitrogen monoxide (NO), CO, carbon dioxide (CO_2), hydrocarbons (HC), and exhaust opacity.

Nevertheless, even if RSD data is not particularly good for assessing emissions of individual vehicles, but rather giving the characteristics of fleets, RSD can be used for vehicle inspection and maintenance purposes to detect, if an individual vehicle has suspiciously high pollutant emissions in real driving, or, inversely, if this vehicle’s after-treatment is well maintained, and thus can it be exempted from inspection.

Furthermore, in US the development and use of system diagnostics (OBD) as means to constantly monitor the condition and functioning of the EAT system has been a pioneering work. The first generation of OBD was introduced in US already in late 1980’s, about two decades ahead compared to Europe, where EOBD became a standard feature as late as in 2001 (SI) and 2004 (CI).

The functionality and performance of OBD-II and EOBD are fairly identical, and apart from assessing the status of the components vital for maintaining low emissions, additional information can be retrieved via OBD. These include e.g. oil temperature, vehicle speed, engine RPM, throttle position, airflow rate, fuel flow rate, coolant temperature, and more. These parameters accessible via the EOBD interface are of the main interest in MODALES. The designed concept is to use these functional parameters for the estimation of the vehicle’s exhaust emissions level, as well as to characterise the driving, by attaching external data retrieval and storing device to a number of cars driven by volunteering motorists. To enable all this, standards covering the physical hardware and software functionality of both the CAN bus and EOBD interface were examined. Furthermore, the structure of the CAN messages was investigated, and finally, the Unified Diagnostic Service (UDS) standard was explored. All this gave necessary abilities to interact with the array of vehicle ECUs and monitor/record a host of emissions-related parameters.

However, the open standard for OBD-purpose only covers a subset of all potentially available data accessible via the EOBD/CAN-interface, but the rest are non-standard, largely OEM specific. Furthermore, EOBD is also relevant only to passenger cars and vans, because HD vehicles have altogether another kind of architecture and set of standards. Thus, in WP4 a serious effort is made to “crack” the messages and attain as large compendium as possible of parameters that are accessible, and can be monitored for simultaneously assess the exhaust emissions levels and characterise the driving patterns of the motorist at the wheel. This fusion of information shall be used for the benefit of the DALED app, to be developed for the purpose of training and helping motorists to drive their particular vehicle in a low-emission style.

Aside the utilisation of the parameters to assess vehicle’s emissions vs. driving characteristics, MODALES aims also to investigate the performance of EOBD to detect malfunctions and deteriorated performance of the EAT system. MODALES is expected to assess, whether a simple EOBD functionality check and DTC retrieval could act as a substitute to physical measurement of harmful exhaust constituents. Furthermore, an improvement in the EOBD performance is also sought after, resulting in higher rate of detection in poorly maintained and/or tampered vehicles with elevated exhaust emissions. However, the review revealed critical flaws in present EOBD. It was found that the system is system is not robust enough regarding tampering. Crucial defects in the current system are that DTCs can be easily cleared using readily available and low-cost communication tools, thus avoiding the entrapment in the PTI. Furthermore, new software can be loaded into the engine control unit (ECU) to increase engine power output and to disable EATS functionalities to alter the system in such a way that it avoids triggering of DTCs.

Task 2.5 and the corresponding Deliverable D2.3 will address the situation of criminalisation of the tampering and restricting in any way the performance of the EAT systems.

The last main theme, potential impact of retrofitted EATS was studied partly by a literature review, but more as a study of data retrieved from specific experiments performed for this very purpose, in order to assess, how different factors, environmental or mechanical, affect the function of retrofitted EATS. The data used in this analysis was collected by a NOx emissions monitoring system that collects live data from the vehicles with the retrofitted EAT system and uploads the information online to a back-office server. The “big data” retrieved for this purpose was collected from nearly 1700 buses, representing three configurations and five different manufacturers. It was expected that an in-depth scrutiny of the collected data would reveal some phenomena that affect the EAT system operation negatively.

Retrofitting of passenger cars with SCR is possible and there are some approved systems on the marker. However, fragmented market and business to consumer -style business model sets limitations. It is difficult to justify retrofitting only by emission reductions, so other incentives like tax reliefs or subsidies are needed. Those instruments could also include parking permits, avoiding tolls and defying driving restrictions at low-emissions zones.

Regarding retrofits for non-road applications, the usage and installation varies a lot. This is setting higher cost for design and testing for approval. Retrofitting same engine, but installed in another application might require retesting and following possible in-use tests. This might raise the development and certification costs make retrofitting non-feasible. If the installed population is only few examples, statistical analysis of emission benefits is also difficult.

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Adapting driver behaviour
for lower emissions

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