Adapting driver behaviour
for lower emissions

MODALES D4.1: Recommendations for a broader use of On-Board Diagnostics (OBD)

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TASK	T4.1: OBD logging
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List of abbreviations and acronyms

Abbreviation	Meaning
AI	Artificial Intelligence
API	Application Programming Interface
CAN	Controller Area Network
CINEA	European Climate, Infrastructure and Environment Executive Agency
CSS3	Cascading Style Sheets
DALED	Driving Assistance app for Low-Emission Driving
DTC	Diagnostic Trouble Codes
DoA	Description of Action
EATS	Emission after Treatment System
EC	European Commission
ECU	Electronic Control Unit
EOBD	European On-Board Diagnostics
EPS	Environmental Protection System
EU	European Union
FMEP	Friction Mean Effective Pressure
FMI	Failure Mode Identifier
FMS	Fleet Management System
FTP	File Transfer Protocol
GPS	Global Positioning System
HDV	Heavy-duty vehicle
HTML5	HyperText Markup Language
ICT	Information and Communication Technologies
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
LDV	Light-duty vehicle
MIL	Malfunction Indicator Light
ML	Machine Learning
NOx	Nitrogen oxides
NRMM	Non-Road Mobile Machinery
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*
OBM	On-Board Monitoring
OBFCM	On-Board Fuel and/or Energy Consumption
OC	Occurrence Counter
OTL	OBD Threshold Limits
OS	Operating System
PCA	Principal Component Analysis
PID	Parameter ID (OBD II)
PGN	Parameter Group Number (J1939)
PTI	Periodic Technical Inspection
RDBMS	Relational Database Management System
REST	Representational State Transfer
RPM	Revolutions Per Minute
SID	Service ID (OBD II)
SPN	Suspect Parameter Numbers (J1939)
t-SNE	t-distributed Stochastic Neighbour Embedding
UDS	Unified Diagnostic Service
URL	Uniform Resource Locator
WCAG	Web Content Accessibility Guidelines
WLTP	Worldwide harmonised Light vehicles Test Procedures
WP	Work Package
XML	Extensible Mark-up Language

Executive Summary

This deliverable considers recommendations for a broader use of On-Board Diagnostics (OBD). The origins of OBD lie in the identification of emission-related deviations to reduce environmental impact. This project foresees the use of data that is accessible via OBD plus additional information from third party devices to identify driver behaviour, which might have an impact on emissions later, as well as on wear and tyre throughout the lifespan.

We began by investigating potentially relevant diagnostic parameter that can be accessed via OBD Identifiers (OBD PIDs), to attempt to gain insights into driving behaviour. On basis of this, we analysed the availability of these PIDs in a random set of cars with different types of fuel and years of manufacture, ranging from 2007 to 2019. The lessons learned were that newer cars support more PIDs but from our list of potentially relevant PIDs, only quite a small number of PID was widely supported. This will have an impact on decisions about what age cars we support in the later field test or on what basis we model driving behaviour.

Before we could perform field test, we needed to spend time in in order to select a suitable OBD dongle. Dongles support different protocols, might contain additional sensors, and are accessed in different ways. Based on a small market study, we identified all potentially relevant properties, from which we selected some that we need to develop our own application.

A deeper look at the modelling of the powertrain, brakes and tyres of a car was done, to identify driving behaviour. These models list some of the properties that might be accessible via OBD or which have to be accessed via additional sensors. If these sensors prove to be emission-relevant, they might be made available in a future OBD standard.

Finally, we discuss the potential recommendations for a broader use of OBD, not only from a legal point of view, but also regarding the lack of available services or the avoidance of vehicle tampering.

1. Introduction

1.1. Project overview

The MODALES project works towards reducing air pollution from all types of on-road vehicles by encouraging the adoption of low-emission driving behaviour and proper maintenance choices.

MODALES pursues a user-centric approach to address all the challenges, which, on the one hand enhance low-emission practices, and on the other hand, suppress high-emission behaviour by researching, developing, and testing several innovative and complementary solutions in four key areas (driver, retrofits, EOBD and inspection) to reduce vehicle emissions from three main sources: powertrain, brakes and tyres.

The scope of vehicles covers all vehicle types, ranging from passenger cars to buses and trucks.

The main activities of MODALES are:

- Measurement of real-world vehicle emissions and driving behaviour to produce accurate correlations between them using advanced mathematical and statistical techniques.
- Exploration of the most advanced technologies for retrofits designed to substantially reduce powertrain emissions from all types of vehicles and validate their effectiveness under different real-world traffic and environment conditions, and by various drivers.
- Undertaking an in-depth analysis of OBDs, periodic inspection and legal issues on tampering in Europe to help regulatory authorities put in place effective anti-tampering legislation, and help owners properly maintain their vehicles.
- Conducting extensive low-emission user trials (with both driving and maintenance practices), supported by awareness campaigns, to enhance public engagement and help drivers better understand the impact of their driving and maintenance behaviours in all situations.

1.2. Scope

This deliverable is part of Work Package 4 (WP4) on the **Effectiveness of inspections and depollution systems**, which is one of the five technical WPs of MODALES (the two “non-technical” WPs include WP1 on Project Management and WP7 on Awareness, Communication and Dissemination). The five “technical” WPs of MODALES are the following:

- **WP2: Defining low-emission factors**, which explores driving behaviour variability using existing available data. This WP delivers a first approach on driving behaviour patterns and powertrain, brake and tyre emissions. It also addresses the state-of-the-art in retrofits, inspection, and maintenance (I/M) and legal issues regarding tampering in various EU member states.
- **WP3: Impact of user behaviours**, which undertakes a series of measurement campaigns to establish the interconnection between driving behaviour and powertrain exhaust emissions, as well as fine particulates from brakes and mass-loss from tyres. Measurement campaigns are also carried out to address the impact of poor maintenance and deliberate tampering of the emission control system.

- **WP4: Effectiveness of inspections and depollution systems**, which uses the findings of WPs 2 and 3 as a basis to investigate and propose solutions that will contribute to emission monitoring via the EOBD protocol and systems that detect a lack of maintenance and tampering. It also investigates the potential of enhancing existing retrofit systems.
- **WP5: Guidelines and tools for low-emission training**, which takes into consideration results from the above WPs in order to define guidelines for low-emission driving and specify the technical requirements for a smartphone application. The app is developed and tested in this WP. A training course area is also designed to ensure consistency with existing learning processes and serve as input for on-road trials and awareness campaigns.
- **WP6: User trials and evaluation**, which develops an evaluation plan to test and evaluate, with real-world trials, the functionality of the innovations developed in MODALES, their effects on driver acceptance and performance and their potential wider impact (their predicted overall effects on vehicle emissions).

The figure below shows how these deliverables fit into the project and highlights related deliverables which will consider the content of this one.

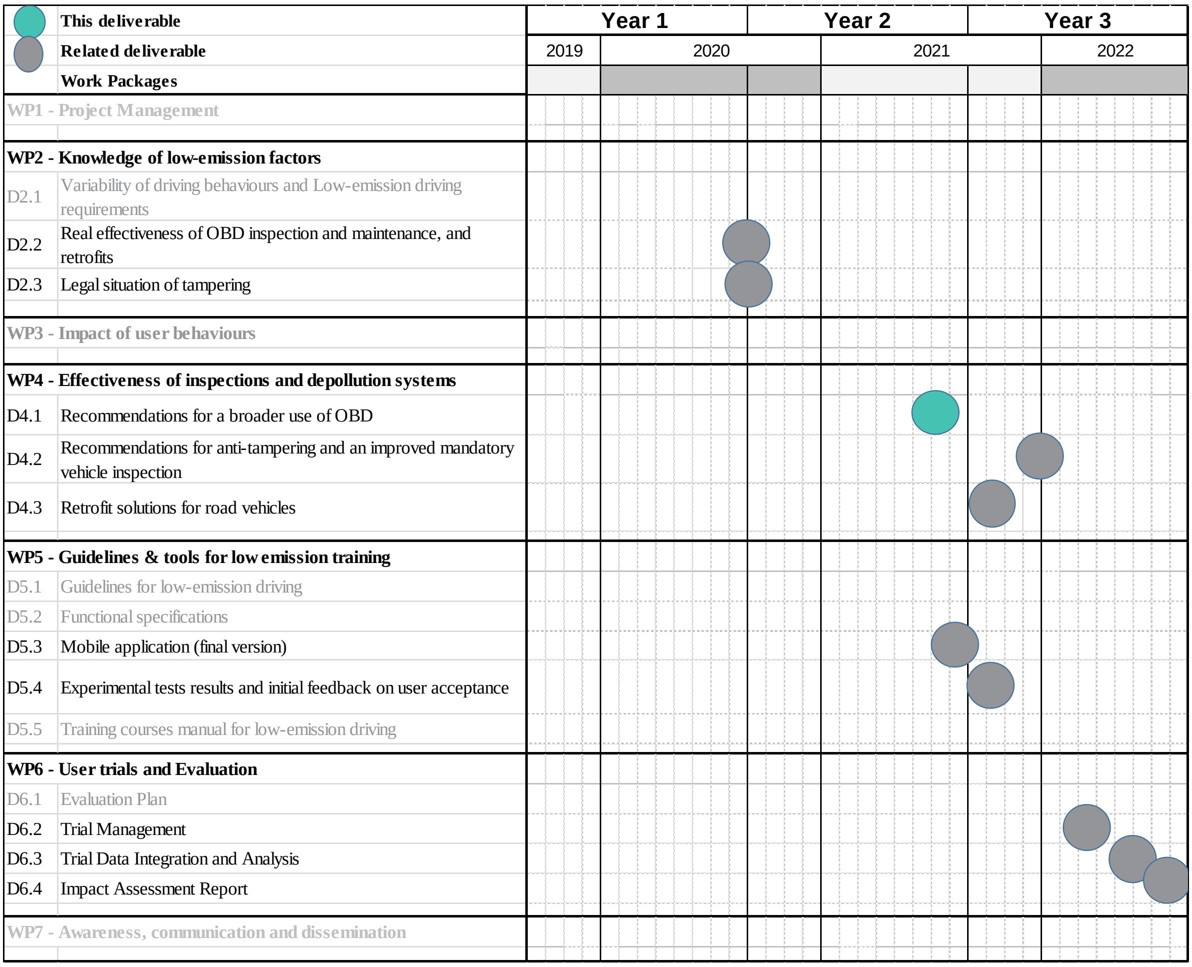

Figure 1: D4.1 in the context of related MODALES tasks and deliverables

1.2.1. MODALES WP4 on the effectiveness of inspections and depollution systems

The aim of the WP is to propose and validate possible solutions that will contribute to lower emissions by involving (a) OBD data, (b) periodic inspections and anti-tampering solutions and (c) retrofits for passenger cars, light- and heavy-duty vehicles (LDVs/HDVs). Taking WP2's findings as inputs, WP4 will:

- Study user behaviours concerning poor maintenance or tampering, taking into account the real effectiveness of OBD and periodic inspections;
- Demonstrate solutions that will allow the detection of poor maintenance and/or tampering;
- Propose regulatory improvements for more rigorous inspection controls all over Europe, together with a tougher sanction system for both vehicle owners and technician violators;
- Investigate the feasibility and potential of retrofit emission controls and expand their practicality to heavy-duty/non-road mobile machinery (NRMM) applications, light-duty trucks and large vans;
- Study and experiment with prototype technologies, not yet released to the market, that will be used to retrofit LDVs/HDVs, targeting a dramatic reduction of NO_x from diesel engines.

This deliverable is the outcome of MODALES Task 4.1 “OBD logging”. The purpose of this task is to investigate how current OBD systems can be used and improved when facing (a) a lack of maintenance or deliberate tampering with a vehicle, and (b) statistical or mathematical models that require a continuous data flow to be supplied. This task will serve as calibration for the development and will provide the software components needed to achieve it.

1.2.2. Scope and intended audience of this deliverable

The content of this deliverable is public.

1.3. Deviations from the Description of Action (DoA)

This deliverable is aligned with the content of the DoA. However, a delay of 4.5 months has been experienced (initial due date: M18, submission date: M22). This is due in particular to three reasons:

- Experiments were foreseen in Task 4.1, to be used as an input for this deliverable. They were delayed due to the COVID-19 pandemic and the limited access to vehicles.
- Part of the deliverable and recommendations to be provided were dependent on WP3, where experiments have also been delayed.
- OBD data was initially supposed to be provided by one of the originally proposed International Partners in China, which in the end did not receive local funding, so in the end this aspect had to be managed by LIST – thus causing a delay.

According to the DoA, the following activities were foreseen for Task 4.1, to which the present deliverable is connected:

- *“The analysis of shortcomings derived from Task 3.4 (and thus Task 2.2), and the implementation of corrective guidelines for improving current vehicle regulations (EOBD)”* → This is covered by the present deliverable. It should also be mentioned that since the first version of the description of action, other projects like DIAS[1] have provided complementary results – referenced in Section 6.

- *"The use of anomaly detection techniques on an extended set of CAN-bus messages to detect interpretation failures from the OBD"* → This deliverable is only focused on higher-level protocols (OBD, J1939). CAN BUS reading will be done in Task 4.2 to compensate the additional work due to dongle selection, experiments and OBD data generation.
- *"The study of the sampling and communication frequencies needed to obtain metrics that can execute the models defined in Task 3.5, which would have been studied in theoretical conditions or by simulation and not necessarily by considering existing technological constraints and regulations"* → This aspect is covered by the present deliverable.
- *"The use of real OBD data, allowing the effect of the working conditions of OBDs on emissions to be analysed and quantified"* → This aspect is addressed, even if the collected data is of limited quantity due to the COVID-19 crisis and the subsequent limited access to vehicles.
- The study of alternatives to retrieve certain metrics, or to interpret indicators related to maintenance or tampering - for example, by using external sensors or phone sensors → this deliverable partly covers this aspect, which is also the object of other MODALES deliverables.
- A test phase, using part of the data collection module from T5.3 to validate the assumptions set for this task. → This is covered.

Finally, it should be noted that this deliverable also contains a very useful description of commercially available OBDs and details the specifications and selection criteria that are important for the MODALES project and the app development (WP5).

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[1] H2020, grant agreement No. 814951, https://dias-project.com

2. OBD logging requirements in MODALES

2.1. Background on OBD logging

All details about OBD logging were discussed in MODALES Deliverable D2.2. “Real effectiveness of OBD inspection and maintenance, and retrofits” [1], Chapter 3 on on-board diagnostics protocols. In brief, we must differentiate between raw logging of CAN frames from the CAN bus, and the logging of OBD/UDS and J1939 messages that are encapsulated in CAN frames. J1939 messages are mainly used in heavy duty vehicles.

The logging of raw CAN messages that are sent between the ECUs only makes sense where the ECUs of the vehicle are known and the message itself can be understood. For all messages that go beyond OBD/UDS and J1939 messages, this is generally not the case.

For OBD/UDS, to understand the communication inside the car or to request information from ECUs, Service IDs (SIDs) with their Parameter IDs (PIDs) must be known. They are standardised in ISO 15031-5 / SAE J1979 for OBD [3] and ISO 14229-1 for UDS. A list of standardised SIDs and PIDs can be found in Wikipedia [1,2]. Also relevant in this context are also the Diagnostic Trouble Codes (DTC), that are standardised in ISO 15031-6/SAE J2012-DA, but which also exist as non-standardised codes of specific brands and models. These codes mainly describe where they occurred, the type of error, the affected sub-system and a description of the error. In our case, we only focused on the standardised SID/PID and DTC.

The equivalents to SIDs and PIDs in J1939 for heavy duty vehicles are Parameter Group Numbers (PNGs) and Suspect Parameter Numbers (SPNs) They are standardised in Part 71 of SAE J1939 [4]. Part 73 [5] of that standard also knows diagnostic trouble codes, but with a different inner structure than the OBD/UDS codes. 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 us how often the error has occurred.

The logging of OBD/UDS or J1939 messages does not require processing of the inner structure of CAN messages. The logging devices (dongles) unpack the information and provide them in a useful way.

2.2. Data requirements

An in-depth description of requirements regarding data was given in Chapter 5 “Data specification” of MODALES Deliverable 5.2: “Functional specifications” [2].

2.2.1. Categories of data

Data that are relevant to the project are grouped into the following categories. Not all data is accessed via OBD/J1939:

Static data that does not change during the trip:

- **Driver profile**

  This is data that gives some rough profiling information of the driver, e.g., age, gender or driving experience. During the collection of data on a trip, all these properties can be considered static. If there is a change of driver during a trip, the driver profile has to change accordingly.

- **Vehicle** collected via OBD/J1939 or which is looked up

  This is data that is specific to the vehicle used during the trip. It includes information, such as the vehicle identification number VIN or the number of kilometres travelled. As a classification criterion, the number of kilometres travelled can be seen as static during a trip. From the VIN, the brand, model, type of vehicle and engine can be looked up.

Data collected during the trip via OBD/J1939 or app:

- **Driving behaviour**

  Data that is directly controlled by the driver, like speed, rpm, acceleration, gear position, gas pedal position, steering wheel angle.
- **Vehicle status**

  Emissions and other sensor information that are a consequence of the driver behaviour.
- **Location**

  The current location of the car. This information is mainly only relevant to look up the data of the next category.

Data looked up during/after the trip:

- **Road and traffic conditions**

  Examples: type of road/road surface, existing speed limit, congestion
- **Weather**

  Everything related to weather conditions, including lighting conditions

2.2.2. Data accessible via OBD/J1939

From the previous list of data categories, only vehicle data, status and driving behaviour are accessible via OBD and J1939. The table in the following pages provides a detailed and extended version of the data listed in the functional specification document: MODALES D5.2 [2], Chapter 5 on relevant data. Sources of the information provided are the Digital Annexe of SAE J1979 [3], SAE J1939 Part 71 [4] and Part 73 [5] and Wikipedia [14].

Table 1: List of relevant OBD and J1939 services

	OBD/UDS								J1939							
Value	**Description**	**SID (hex)**	**PID (hex)**	**Bytes**	**Min**	**Max**	**Unit**	**Resolution, Offset, Formula**	**Description**	**PGN (dec)**	**SPN (dec)**	**Bytes**	**Min**	**Max**	**Unit**	**Resolution, Offset, Formula**
VIN	Vehicle Identification Number (VIN)	9	02	17	17-char VIN, ASCII-encoded and left-padded with null chars (0x00) if needed.				Vehicle Identification Number	65260	237	Variable - up to 200 characters - "*" is the delimited	-	-	-	-
Gear	Transmission Actual Gear Status Supported	1	A4	4	A0=1: Actual transmission of gear supported A1=1: Actual transmission of gear ratio supported				Current Gear	61441	523	1	-125	125	#Gear	1 gear value per bit -125 offset A-125
	Transmission Actual Gear Status				0	15	#Gear	B (1=reverse)								
	Transmission Actual Gear Ratio				0	65.535	ratio input shaft speed to output shaft speed	0.001 per bit 0 offset $(C*2^8+D)/1000$								
Gas pedal	Accelerator Pedal Position (Absolute / Relative)	1	49 4A 4B 5A	1	0	100	%	100/255 % per bit 0% offset (100/255)*A	Accelerator Pedal Position 1	61443	91	1	0	100	%	0.4% per bit 0% offset A/2.5
Throttle	Throttle Position (Absolute / Relative)	1	11 47 48 8D 45	1	0	100	%	100/255 % per bit 0% offset (100/255)*A	Throttle Position	65266	51	1	0	100	%	0.4% per bit 0% offset A/2.5
Brake pedal	-	-	-	-	-	-	-	-	Brake Pedal Position	61441	521	1	0	100	%	0.4% per bit 0% offset A/2.5
Steering wheel	-	-	-	-	-	-	-	-	Steering Wheel Angle	61449	1802	2	-31.374	31.374	rad	1/1024 rad per bit -31.374 rad offset A/1024-31.374
									Steering Wheel Turn Counter	61449	1811	6 bits	-32	29	turns	1 turn/bit -32 turns offset operating range -10 to 10 A-32
Speed	Vehicle Speed	1	0D	1	0	255	km/h	1 km/h per bit 0 km/h offset A	Tachograph vehicle speed	65132	1624	2	0	250.996	km/h	1/256 km/h per bit 0 km/h offset $(A*2^8+B)/256$
									Wheel-Based Vehicle Speed	65265	84	2	0	250.996	km/h	1/256 km/h per bit 0 km/h offset $(A*2^8+B)/256$
RPM	Engine RPM	1	0C	2	0	16,383.75	rpm	0.25 rpm per bit 0 rpm offset $(A*2^8+B)/4$	Engine Speed	61444	190	2	0	8,031.875	rpm	0.125 rpm per bit 0 rpm offset $(A*2^8+B)/8$

Table1: List of relevant OBD and J1939 services (continued)

	OBD/UDS								J1939							
Value	**Description**	**SID (hex)**	**PID (hex)**	**Bytes**	**Min**	**Max**	**Unit**	**Resolution, Offset, Formula**	**Description**	**PGN (dec)**	**SPN (dec)**	**Bytes**	**Min**	**Max**	**Unit**	**Resolution, Offset, Formula**
Accelera-tion	-	-	-	-	-	-	-	-	Yaw Rate	61449	1808	2	-3.92	3.92	rad/s	1/8192 rad/s per bit -3.92 rad/s offset (A*2^{8}+B)/ 8192-3.92
									Lateral Acceleration	61449	1809	2	-15.687	15.687	m/s#	1/2048 m/s# per bit -15.687 m/s# offset (A*2^{8}+B)/ 2048-15.687
									Longitudinal Acceleration	61449	1810	1	-12.5	12.5	m/s#	0.1 m/s# per bit -12.5 m/s# offset A/10-12.5
Torque	Driver's Demand Engine - Percent Torque	1	61	1	-125	130	%	1% per bit -125% offset A-125	Driver's Demand Engine - Percent Torque	61444	512	1	-125	125	%	1 %/bit -125% offset
	Actual Engine - Percent Torque	1	62	1	-125	130	%	1% per bit -125% offset A-125	Actual Engine - Percent Torque	61444	513	1	-125	125	%	1 %/bit -125% offset A-125
Engine Power	-	-	-	-	-	-	-	-	Rated Engine Power	65214	166	2	0	32,127.5	kW	0.5 kW/bit 0 kW offset (A*2^{8}+B)/2
Fuel Consum-ption	Engine Fuel Rate	1	5E	2	0	3,212.75	L/h	0.05 L/h per bit 0 L/h offset (A*2^{8}+B)/ 20	Trip Fuel	65257	182	4	0	2,105,540.607.5	L	0.5 L/bit 0 /bit offset (A*2^{24}+ B*2^{16}+C*2^{8} +D)/2
									Fuel Rate	65266	183	2	0	3,212.75	L/h	0.05 L/h per bit 0 offset (A*2^{8}+B)/2 0
	Engine Fuel Rate	1	9D	4	0	1,310.7	g/s	0.02 g/s per bit 0 g/s offset (A*2^{8}+B)/ 50	Instantaneous Fuel Economy	65266	184	2	0	125.5	km/kg	1/512 km/kg per bit 0 km/kg offset (A*2^{8}+B)/ 512
	Vehicle Fuel Rate							0.02 g/s per bit 0 g/s offset (C*2^{8}+D)/ 50	Average Fuel Economy	65266	185	2	0	125.5	km/kg	1/512 km/kg per bit 0 km/kg offset (A*2^{8}+B)/ 512

Table1: List of relevant OBD and J1939 services (continued)

	OBD/UDS								J1939							
Value	Description	SID (hex)	PID (hex)	Bytes	Min	Max	Unit	Resolution, Offset, Formula	Description	PGN (dec)	SPN (dec)	Bytes	Min	Max	Unit	Resolution, Offset, Formula
Mass Air Flow	Mass Air Flow Sensor (MAF) Air Flow Rate	1	10	2	0	655.35	g/s	0.01 g/s per bit 0 g/s offset (A*2^8+B)/100	Inlet Air Mass Flow Rate	61450	132	2	0	3,212.75	kg/h	0.05 kg/h per bit 0 km/h offset (A*2^8+B)/20
									Mass Flow (Gaseous)	65170	1241	2	0	3,212.75	kg/h	0.05 kg/h per bit 0 kg/h offset (A*2^8+B)/20
	Mass Air Flow Sensor Support	1	66	5	A0=1: MAF Sensor A data supported A1=1: MAF Sensor B data supported				Fuel Flow Rate 1	65153	1440	2	0	6,425.5	m^3/h	0.1 m^3/h per bit 0 m^3/h offset A/10
	Mass Air Flow Sensor A				0	2,047.96875	g/s	0.03125 g/s per bit 0 g/s offset (B*2^8+C)/32	Fuel Flow Rate 2	65153	1441	2	0	6,425.5	m^3/h	0.1 m^3/h per bit 0 m^3/h offset A/10
	Mass Air Flow Sensor B							0.03125 g/s per bit 0 g/s offset (D*2^8+C)/32								
Air Pressure	Absolute Barometric Pressure	1	33	1	0	255	kPa	1 kPa per bit 0 kPa offset A	Barometric Pressure	65269	108	1	0	125	kPa	0.5 kPa/bit 0 kPa offset A/2
Temperature	Ambient Air Temperature	1	46	1	-40	215	°C	1 °C per bit -40 °C offset A-40	Cab Interior Temperature	65269	170	2	-273	1,735	°C	0.03125 °C/bit -273 °C offset (A*2^8+B)/32-273
									Ambient Air Temperature	65269	171	2	-273	1,735	°C	0.03125 °C/bit -273 °C offset (A*2^8+B)/32-273
	Intake Air Temperature Sensor Support	1	68	7	A0=1: Bank 1, Sensor 1 supported A1=1: Bank 1, Sensor 2 supported A2=1: Bank 1, Sensor 3 supported A3=1: Bank 2, Sensor 1 supported A4=1: Bank 2, Sensor 2 supported A5=1: Bank 2, Sensor 3 supported				Air Inlet Temperature	65269	172	1	-40	210	°C	1 °C/bit -40 °C offset A-40
	Intake Air Temperature Bank 1, Sensor 1				-40	215	°C	1 °C per bit -40 °C offset B-40								
	Intake Air Temperature Bank 1, Sensor 2							1 °C per bit -40 °C offset C-40								
	Intake Air Temperature Bank 1, Sensor 3							1 °C per bit -40 °C offset D-40								
	Intake Air Temperature Bank 2, Sensor 1							1 °C per bit -40 °C offset E-40								
	Intake Air Temperature Bank 1, Sensor 2							1 °C per bit -40 °C offset F-40								
	Intake Air Temperature Bank 1, Sensor 3							1 °C per bit -40 °C offset G-40								
	Engine Coolant temperature	1	05	1	-40	215	°C	1 °C per bit -40 °C offset A-40	Engine Coolant Temperature	65262	110	1	-40	210	°C	1 °C/bit -40 °C offset A-40
	Catalyst Temperature (Bank 1+2 Sensor 1+2)	1	3C 3D 3E 3F	2	-40	6,513.5	°C	0.1 °C per bit -40 °C offset (A*2^8+B)/10-40	-	-	-	-	-	-	-	-

Table1: List of relevant OBD and J1939 services (continued)

	OBD/UDS								J1939							
Value	Description	SID (hex)	PID (hex)	Bytes	Min	Max	Unit	Resolution, Offset, Formula	Description	PGN (dec)	SPN (dec)	Bytes	Min	Max	Unit	Resolution, Offset, Formula
NOx	NOx Sensor Support	1	83	9	A0=1: Bank 1, Sensor 1 supported A1=1: Bank 1, Sensor 2 supported A2=1: Bank 2, Sensor 1 supported A3=1: Bank 2, Sensor 2 supported A4=1: Bank 1, Sensor 1 No sensor fault, no results available A5=1: Bank 1, Sensor 2 No sensor fault, no results available A6=1: Bank 2, Sensor 1 No sensor fault, no results available A7=1: Bank 2, Sensor 2 No sensor fault, no results available				-	-	-	-	-	-	-	-
	NOx Sensor Concentration Bank 1 Sensor 1				0	6,5535	ppm	1 ppm per bit 0 ppm offset (B*256+C)								
	NOx Sensor Concentration Bank 1 Sensor 2							1 ppm per bit 0 ppm offset (D*256+E)								
	NOx Sensor Concentration Bank 2 Sensor 1							1 ppm per bit 0 ppm offset (F*256+G)								
	NOx Sensor Concentration Bank 2 Sensor 2							1 ppm per bit 0 ppm offset (H*256+I)								
	NOx Sensor Corrected Support	1	A1	9	A0=1: Bank 1, Sensor 1 supported A1=1: Bank 1, Sensor 2 supported A2=1: Bank 2, Sensor 1 supported A3=1: Bank 2, Sensor 2 supported A4=1: Bank 1, Sensor 1 - No sensor fault, no results available A5=1: Bank 1, Sensor 2 - No sensor fault, no results available A6=1: Bank 2, Sensor 1 - No sensor fault, no results available A7=1: Bank 2, Sensor 2 - No sensor fault, no results available											
	NOx Sensor Corrected Concentration Bank 1 Sensor 1				0	6,5535	ppm	1 ppm per bit 0 ppm offset (B*256+C)								
	NOx Sensor Corrected Concentration Bank 1 Sensor 2							1 ppm per bit 0 ppm offset (D*256+E)								
	NOx Sensor Corrected Concentration Bank 2 Sensor 1							1 ppm per bit 0 ppm offset (F*256+G)								
	NOx Sensor Corrected Concentration Bank 2 Sensor 2							1 ppm per bit 0 ppm offset (H*256+I)								

Table1: List of relevant OBD and J1939 services (continued)

	OBD/UDS								J1939							
Value	Description	SID (hex)	PID (hex)	Bytes	Min	Max	Unit	Resolution, Offset, Formula	Description	PGN (dec)	SPN (dec)	Bytes	Min	Max	Unit	Resolution, Offset, Formula
Diesel particulate Filter (DPF)	Support of PF Bank 1 System Data	1	7A	7	A0=1: PF Bank 1 Delta Pressure data supported A1=1: PF Bank 1 Inlet Pressure data supported A2=1: PF Bank 1 Outlet Pressure data supported											
	Particulate Filter Bank 1 Delta Pressure				-327.68	327.67	kPa	0.01 kPa per bit signed -327.68 kPa offset ((B-128)*256 +C)/100								
	Particulate Filter Bank 1 Inlet Pressure				0	655.34	kPa	0.01 kPa per bit 0 kPa offset (D*256+E)/100								
	Particulate Filter Bank 1 Outlet Pressure				0	655.34	kPa	0.01 kPa per bit 0 kPa offset (F*256+G)/100								
	Support of PF Bank 2 System Data	1	7B	7	A0=1: PF Bank 2 Delta Pressure data supported A1=1: PF Bank 2 Inlet Pressure data supported A2=1: PF Bank 2 Outlet Pressure data supported											
	Particulate Filter Bank 2 Delta Pressure				-327.68	327.67	kPa	0.01 kPa per bit signed -327.68 kPa offset ((B-128)*256+C)/100								
	Particulate Filter Bank 2 Inlet Pressure				0	655.34	kPa	0.01 kPa per bit 0 kPa offset (D*256+E)/100								
	Particulate Filter Bank 2 Outlet Pressure				0	655.34	kPa	0.01 kPa per bit 0 kPa offset (F*256+G)/100								
	Support of Particulate Filter Temperature Data	1	7C	9	A0=1: PF Bank 1 Inlet Temperature data supported A1=1: PF Bank 1 Outlet Temperature data supported A2=1: PF Bank 2 Inlet Temperature data supported A3=1: PF Bank 2 Outlet Temperature data supported											
	Particulate Filter Bank 1 Inlet Temperature Sensor				-40	6513.5	°C	0.1 °C per bit -40 °C offset (B*256+C)/10-40								
	Particulate Filter Bank 1 Outlet Temperature Sensor				-40	6513.5	°C	0.1 °C per bit -40 °C offset (D*256+E)/10-40								
	Particulate Filter Bank 2 Inlet Temperature Sensor				-40	6513.5	°C	0.1 °C per bit -40 °C offset (F*256+G)/10-40								
	Particulate Filter Bank 2 Outlet Temperature Sensor				-40	6513.5	°C	0.1 °C per bit -40 °C offset (H*256+I)/10-40								

Table1: List of relevant OBD and J1939 services (continued)

	OBD/UDS								J1939							
Value	Description	SID (hex)	PID (hex)	Bytes	Min	Max	Unit	Resolution, Offset, Formula	Description	PGN (dec)	SPN (dec)	Bytes	Min	Max	Unit	Resolution, Offset, Formula
Trouble Codes	Request trouble codes	3	-	n *6	3 codes per message frame: A7 A6 trouble code sub-system 00: P - Powertrain 01: C - Chassis 10: B - Body 11: U - Network A5 A4 type of code 00: Generic OBD (ISO/SAE) 01: Manufacturer specific A3 A2 A1 A0 affected sub-system 0001: Fuel and air metering 0010: Fuel and air metering (injector circuit) 0011: Ignition system or misfire 0100: Auxiliary emission controls 0101: Vehicle speed control and idle control system 0110: Computer output circuit 0111-1001: Transmission system A-C: Hybrid propulsion B specific code				Diagnostic Message 1 (DM1) Active DTCs	65226	-	6	Lamp status: A7 A6 Malfunction Indicator Lamp Status A5 A4 Red Stop Lamp Status A3 A2 Amber Warning Lamp Status A1 A0 Protect Lamp Status B7 B6 Flash Malfunction Indicator Lamp B5 B4 Flash Red Stop Lamp B3 B2 Flash Amber Warning Lamp B1 B0 Flash Protect Lamp Interpretation of the two bits depend on the SPN and the combination of Lamp status and flash. Diagnostic Trouble Code: C D E7..E5 SPN E4..E0 FMI (failure mode identifier) F7 SPN Conversion Method 0: Version 4 (recommended) 1: Version 1-3 (until Feb. 1996, no longer permitted) F6..F0 Occurrence Count 127=not available			
									Diagnostic Message 2 (DM2) Previously Active DTCs	65227 59904 (req.)	-	6				
									Diagnostic Message 12 (DM12) Emission Related Active DTCs	65236 59904 (req.)	-	6				
	Clear trouble codes / malfunction indicator lamp (MIL) / check engine light	4	-	0	-			Clears all stored trouble codes and turns the MIL off.	Diagnostic Message 3 / 11 (DM3/DM11) Diagnostics Data Clear of Previously Active DTCs	65228 65235	-	8	all FF			Clears all diagnostic information related to previously active DTCs

3. Comparative analysis and hardware selection

3.1. Brands and models of OBD dongles in the market

The market offers a huge number of OBD dongles from various brands. Our investigation (until July 2020) was mainly driven by the need to identify properties that dongles might have and to identify one or two dongles that provide the properties that we need in our project. We do not claim to have investigated every available dongle in the market, nor do we suggest that the investigated models are superior to those not mentioned.

Table 2: List of current OBD dongles with their variants (as of July 2020)

Brand / Product	Link
OpenXCP	http://openxcplatform.com/
Ford Reference VI	http://openxcplatform.com/vehicle-interface/hardware.html#ford-reference-design
CrossChasm C5 BT	http://openxcplatform.com/vehicle-interface/hardware.html#crosschasm-c5-bt
CrossChasm C5 Cellular	http://openxcplatform.com/vehicle-interface/hardware.html#crosschasm-c5-cellular
CrossChasm C5 BLE	http://openxcplatform.com/vehicle-interface/hardware.html#crosschasm-c5-ble
DIY chipKIT-based VI	http://openxcplatform.com/vehicle-interface/hardware.html#diy-chipkit
Freematics	https://freematics.com/products/
Freematics ONE	https://freematics.com/products/freematics-one/
Freematics ONE+ Model A	https://freematics.com/products/freematics-one-plus/
Freematics ONE+ Model B	https://freematics.com/products/freematics-one-plus-model-b/
Freematics ONE+ Model H	https://freematics.com/products/freematics-one-plus-model-h/
Freematics OBD-II UART Adapter V2.1 (for Arduino)	https://freematics.com/products/freematics-obd-ii-uart-adapter-mk2
Freematics OBD-II I2C Adapter (for Arduino)	https://freematics.com/products/arduino-obd-adapter/
OBDLink	https://www.obdlink.com
OBDLink MX+	https://www.obdlink.com/mxp/
OBDLink MX BlueTooth	https://www.obdlink.com/mxbt/
OBDLink LX BlueTooth	https://www.obdlink.com/lxbt/
OBDLink EX	https://www.obdlink.com/ex/
OBDLink SX	https://www.obdlink.com/sxusb/
CSS Electronic	https://www.csselectronics.com
CANedge1	https://www.csselectronics.com/screen/product/can-logger-sd-canedge1/language/en
CANedge2	https://www.csselectronics.com/screen/product/can-lin-logger-wifi-canedge2/language/en
CL1000	https://www.csselectronics.com/screen/product/can-bus-logger-canlogger1000
CL2000	https://www.csselectronics.com/screen/product/can-bus-logger-canlogger2000
CL3000	https://www.csselectronics.com/screen/product/can-bus-logger-canlogger3000
Simma Software	http://www.simmasoftware.com/j1939-adapter-j1708.html
VNA2-ELD	http://www.simmasoftware.com/eld-brochure.pdf
VNA-232	http://www.simmasoftware.com/j1939-to-rs232.pdf
VNA-USB	http://www.simmasoftware.com/j1939-to-usb.pdf
VNA-WiFi	http://www.simmasoftware.com/wireless-j1939-to-wifi.pdf
VNA2-BT	http://www.simmasoftware.com/wireless-j1939-to-bluetooth.pdf
Pace	https://www.pace.car/de
Pace Link	
LAWICEL	
CANUSB	https://www.obd-2.de/shop/can-bus/20/can-car-sniffer-kit
comma.ai	https://comma.ai/
panda OBD II Interface (white)	https://comma.ai/shop/products/panda-obd-ii-dongle
panda OBD II Interface (grey)	https://comma.ai/shop/products/panda-obd-ii-dongle

Dongles of a particular brand are often provided in various variants or models that mainly differ in the access interface, e.g., Bluetooth Cellular, RS232, but which are otherwise the same. There are also a huge number of dongles in the market that are all based on the ELM327 chipset, or which provide compatibility with the ELM327 commands. Not all of these existing models have been explicitly mentioned, as they all provide the same features. Representatives of these dongles in Table 2 are the Freematics ODB-II models and OBD-Link models.

Characteristics of ODB dongles

From the dongles in the list, it is possible to identify several characteristics that a dongle might have.

3.1.1. Supported standards

There are three main standards that are relevant and that might be supported by the dongles:

- OBD II for cars
- J1939 for heavy duty vehicles
- Raw CAN for all types of vehicles

A dongle might support one or more of these standards.

A special aspect in relation to OBD II is the support of vendor-specific codes. This is not a feature of the hardware itself, but mainly a feature of the software that manages the device. If the software can interpret a vendor-specific code, it is able to provide additional information to the users about the inner state of the vehicle. The interpretation of the vendor-specific PID is only possible if the vendor communicates the required information. This is normally not available to the public. Most of the vendors are members of the Equipment and Tool Institute, to which access is granted with an annual subscription. Unfortunately, not all vendors are organised in this way, so additional fees may be encountered by brands that manage the information themselves.

3.1.2. Main connector

There are two main types of dongle connectors:

- The OBD II connector provides access to the OBD connector in cars.
- The OBD II Type B connector provides access mainly to heavy-duty vehicles. It is designed in such a way that a Type B dongle can be plugged in to cars, but the standard connector does not connect to the interface of heavy-duty vehicles. The reason for this is that the power provided in both types of vehicles is different and would destroy standard dongles plugged into heavy-duty vehicles.
- DB9 or DB15 connectors are used to provide dongles that are independent of the connector on the vehicle side. An additional cable is required to bridge the DB9 or DB15 interface with the interface at the vehicle.

3.1.3. Accepted maximal power

As already mentioned in the previous section, heavy duty vehicles provide a different voltage to cars via the OBD II connector:

- 12 V is the power provided to the OBD II dongle for cars.
- 24 V is the power provided to the OBD II Type B dongle for heavy-duty vehicles.

Some dongles are able to accept both power levels and even a higher maximal power (e.g., 30V, 60V) without risking damage.

3.1.4. Interfaces

Beside the main connector interfaces, dongles provide additional interfaces to access the device or to exchange data, which are either wireless, wired or use local storage:

- Wireless:
    - Bluetooth/Bluetooth Low Energy
    - WiFi
    - Cellular (GSM/UMTS (3G) /LTE (4G))
- Wired:
    - USB
    - DB9/RS-232
    - I^2C
    - UART
- Local storage:
    - SD Card

3.1.5. Programming, configuration

Several dongles provide access to the device that go beyond the given software bundled with the device. Some provide developer libraries that support access being bound into software that is developed individually, while others require accessing the device by sending direct commands via virtual com-ports via USB, UART or I^2C:

- The OpenXC library is the library used for the OpenXCP devices. Libraries exist for Android, iOS and Python.
- The Ardunio IDE library in C is used to access Freematics devices.
- PlatformIO allows firmware to be created for the Freematics devices with Atom or Visual Studio Code.
- With the ELM327 AT command set, the device can be directly accessed without the use of libraries. This is possible for OBDLink devices or any ELM327-based clone. For OBDLink, an extended ST command set is provided in addition to the standard AT commands.
- Various libraries are available for ELM327 compatible dongles, e.g., Python, JavaScript, go, Java, etc.
- The D2XX-Modus DLL or ActiveX-Controls provide an option to submit ASCII commands via a virtual com-port.
- Finally, the Simma VNA dongles use RS-232 messages to exchange information.

3.1.6. Data exchange formats

Configured dongles need to provide the requested data in a machine-readable way. There are several ways of doing this currently in use by the different dongles to pack the data inside a data structure:

- ASCII
- JSON
- Binary (Google Protocol Buffers)
- Message Pack
- Trace File Format
- ASAM MDF4
- CSV

3.1.7. Additional features

If a constant log of information is recorded, the circumstances of this information are quite important and mainly include when it was logged and where the vehicle was at that time. The "when", requires a clock that either is provided by a built-in real-time clock or by reading the time information provided by the GPS signal, if available. Additional information that can be useful is the acceleration (G-Force) or the orientation of the vehicle in the 3D space. The following short list summarises these elements:

- Current Time via Real Time Clock
- Geolocation via GPS
- G-Force via Accelerometer
- Orientation via Gyroscope

3.2. Competitive matrix

In the following table, all dongles analysed are listed with their identified characteristics.

Table 3: Characteristics of dongles

Brand Product	Features	Raw CAN	OBD	J1939	vendor-specific codes	max. Power accepted	Main Connector	Exchange Format	Real Time Clock	Commands	Interface	Developer library / supported languages
Legend: +=yes; -=no; ?=unknown; (+)=likely yes; (-)=likely no; BT=Bluetooth; BLE=Bluetooth Low Energy; SD=SD Card;												
OpenXCP												
Ford Reference VI		+	+	-	?	12V	OBD II	JSON Binary (Google Protocol Buffers) Message Pack Trace File Format	-		BT	OpenXC library (Python, Android, iOS)
CrossChasm C5 BT		+	+	-	?	12V	OBD II	JSON Binary (Google Protocol Buffers) Message Pack Trace File Format	+		BT, SD	OpenXC library (Python, Android, iOS)
CrossChasm C5 Cellular		+	+	-	?	12V	OBD II	JSON Binary (Google Protocol Buffers) Message Pack Trace File Format	+		3G, GPS, SD	OpenXC library (Python, Android, iOS)

Table 3: Characteristics of dongles (continued)

Brand Product	Features	Raw CAN	OBD	J1939	vendor-specific codes	max. Power accepted	Main Connector	Exchange Format	Real Time Clock	Commands	Interface	Developer library / supported languages
Legend: +=yes; -=no; ?=unknown; (+)=likely yes; (-)=likely no; BT=Bluetooth; BLE=Bluetooth Low Energy; SD=SD Card;												
CrossChasm C5 BLE		+	+	-	?	12V	OBD II	JSON Binary (Google Protocol Buffers) Message Pack Trace File Format	+		BLE	OpenXC library (Python, Android, iOS)
DIY chipKIT-based VI		+	+	-	?	12V	OBD II	JSON Binary (Google Protocol Buffers) Message Pack Trace File Format	+		BT	OpenXC library (Python, Android, iOS)
Freematics												
Freematics ONE	G-Force Orientation	-	+	-	-	12V	OBD II		-		SD, BLE (opt), GPS (opt), USB	Firmware-Development: PlatformIO IDE Ardunio IDE (library) / C
Freematics ONE+ Model A	G-Force Orientation	+	+	-	-	12V	OBD II		+		SD, BT, BLE, WiFi, GNSS (opt), GSM/UMTS (opt), LTE (opt), USB, 2*GPIO	Firmware-Development: PlatformIO IDE Ardunio IDE (library) / C
Freematics ONE+ Model B	G-Force Orientation Geolocation	+	+	-	-	12V	OBD II		+		SD, BT, BLE, WiFi, GNSS, GSM/UMT, LTE, USB, 2*GPIO	Firmware-Development: PlatformIO IDE Ardunio IDE (library) / C
Freematics ONE+ Model H	G-Force Orientation Geolocation	+	+	+	-	60V	OBD II Type B		+		SD, BT, BLE, WiFi, GNSS, GSM/UMT, LTE, USB, 2*GPIO	Firmware-Development: PlatformIO IDE Ardunio IDE (library) / C
Freematics OBD-II UART Adapter V2.1 (for Arduino)		+	+	-	-	12V	OBD II		-	ELM327 AT	UART, USB	Ardunio library / C
Freematics OBD-II I2C Adapter (for Arduino)		-	+	-	-	12V	OBD II		-	ELM327 AT	I^{2}C	Ardunio library / C
OBDLink												
OBDLink MX+		-	+	-	Ford GM	12V	OBD II		-	ELM327 AT / ST Extension	BT	
OBDLink MX BlueTooth		-	+	-	Ford GM	12V	OBD II		-	ELM327 AT ST Extension	BT	
OBDLink LX BlueTooth		-	+	-	-	12V	OBD II		-	ELM327 AT ST Extension	BT	
OBDLink EX		-	+	-	Ford	12V	OBD II		-	ELM327 AT ST Extension	USB	
OBDLink SX		-	+	-	-	12V	OBD II		-	ELM327 AT ST Extension	USB	
CSS Electronic												
CANedge1	Supports free firmware updates for adding features	+	(+)	(+)	-	32V	2 * DB9	ASAM MDF4	+		SD	
CANedge2	Supports free firmware updates for adding features	+	(+)	(+)	-	32V	2 * DB9	ASAM MDF4	+		SD, WiFi, GSM/UMTS (opt)	
CL1000	Supports free firmware updates for adding features	+	+	+	-	36V	DB9	CSV	-		SD, USB	

Table 3: Characteristics of dongles (continued)

Brand Product	Features	Raw CAN	OBD	J1939	vendor-specific codes	max. Power accepted	Main Connector	Exchange Format	Real Time Clock	Commands	Interface	Developer library / supported languages
Legend: +=yes; -=no; ?=unknown; (+)=likely yes; (-)=likely no; BT=Bluetooth; BLE=Bluetooth Low Energy; SD=SD Card;												
CL2000	Supports free firmware updates for adding features	+	+	+	-	36V	DB9	CSV	+		SD, USB	
CL3000	Supports free firmware updates for adding features	+	+	+	-	36V	DB9	CSV	+		SD, USB, WiFi, GSM/UMTS (opt)	
Simma Software												
VNA2-ELD		+	+	+	?	30V	DB15			RS-232 messages	BT, BLE, RS-232, GPS (otp)	
VNA-232		+	-	+	?	30V	DB15			RS-232 messages	RS-232	
VNA-USB		+	-	+	?	30V	DB15			RS-232 messages	USB	
VNA-WiFi		+	-	+	?	30V	DB15			RS-232 messages	WiFi	
VNA2-BT		+	-	+	?	30V	DB15			RS-232 messages	BT	
Pace												
Pace Link		-	+	-	-	12V	OBD II				BT	
LAWICEL												
CANUSB		+	-	-	-	12V	DB9	CSV	+	Virtual COM Port: ASCII Commands	USB	D2XX-Modus / DLL ActiveX-Control
comma.ai												
panda OBD II Interface (white)		-	+	-	+	12V	OBD II				USB, WiFi	JS, Python
panda OBD II Interface (grey)		-	+	-	+	12V	OBD II				USB, GPS	JS, Python

3.3. Selection of OBD dongles for MODALES and key specifications

In the selection process, we identified several characterises that a dongle should have. Table 4 on the next page gives an overview about the criteria, that might be relevant. It is useful to select two dongles, one for cars and one for heavy-duty vehicles, where the data exchange format, the commands and the libraries for both models are identical. The "Required" column in the table indicates, if either "all" properties in the list should be supported or only "one".

From the list of all available dongles that fulfil the requirements, we did a pre-selection. First the dongle should be affordable. In the project we might buy a huge number of dongles for the field-test and higher price is only accepted if the reasons justify that price. Second, we need to be able to develop software for the dongle. Existing libraries that are easy to use and learn and which allow to configure the device to our needs are a plus. On base of that we decided to go for ELM327 compatible OBDLink dongles, that have a wide range of software support. Alternatively, we decided to try the Freematics ONE dongles, that provide a development environment, but more important, are shipped in two versions from which the one version supports heavy duty vehicles with a OBD II Type B connector and ≥ 24V support.

On base of that choice, we bought these dongles an tested the way they can be programmed and configured. Additionally, we tried to identify technical details which that are not obvious in the technical specifications, but which might affect the useability of the dongles.

Table 4: Selection criteria and potential candidates

				Potential Dongles		
Characteristics	Car	Heavy-duty vehicle	Required	ELM327 compatible	OBDLink (MX+, LX)	Freematics One+ (Model B, Model H)
Supported protocols	Raw CAN OBD	Raw CAN J1939	all	Raw CAN OBD J1939	Raw CAN OBD J1939	Raw CAN OBD J1939 (H)
Accepted maximal voltage	≥ 12V	≥ 24V for J1939		12V	12V	12V (B) ≥ 24V (H)
Main connector	OBD II Type A	OBD II Type B for J1939		OBD II Type A OBD II Type B for J1939	OBD II Type A	OBD II Type A (B) OBD II Type B (H)
Interfaces	Bluetooth Low Energy Bluetooth WiFi USB LTE/4G SD / ROM (on-unit logging)		one	Bluetooth	Bluetooth (MX+, LX)	BLE/BT WiFi USB LTE/4G SD / ROM (on-unit logging)
Features	Geolocation/GPS G-Force Accelerometer Orientation Real Time Clock			-	-	Geolocation/GPS G-Force Accelerometer Orientation Real Time Clock
Data Exchange Format	JSON CSV non-proprietary		one	non-proprietary	non-proprietary	custom programmable
Commands	ELM327 AT/ST documented		one	ELM327 AT	ELM327 AT/ST	custom programmable
Developer Libraries	NodeJS Python Flutter Ionic support		one	broadest support all important languages	broadest support all important languages	custom programmable

3.4. Remarks about the selected dongles

As seen in the previous table, the OBDLink models are ELM327-compatible dongles. However, it is worth mentioning some differences of ELM327 compatible dongles:

- For CAN sniffing, the internal buffer of some ELM327 dongles is too small, running the risk of losing messages.
- Many models are only compatible with Android.
- J1939 support, seems working on latest official chip sets, only.
- The market for ELM327 dongles seems to be highly saturated with counterfeit products. Genuine products are hard to identify.

OBDlink provides the model MX+ and LX which are worth considering:

- A power-saving mechanism is available ensuring that the car battery does not discharge too fast when the car is not being used.
- The LX model is only Android-compatible.
- The MX+ model is also MFI-certified to work with Apple iOS.

Freematics provides model B, which is intended for cars only and model H, which is also usable for heavy-duty vehicles.

- The GPS reading is not reliable but can be improved by an external GPS antenna or a different location of the dongle in the vehicle in combination with an OBD extension cord.

- A power-saving mechanism is available.
- PGNs can be received if the port is not already blocked by Fleet Management System (FMS) and the FMS-port has already been enabled by the manufacturer.

For all dongles tested, their size is a problem. When installed in the OBD-II port, they are potentially too long to be used during driving. The cover cannot be fully closed, which makes them unsuitable for daily use. Limited ELM327 dongles are available in a "short" version. One option to solve the problem is to use a 90° flat cable to angle the dongle differently. This might also solve the GPS problem.

A second problem is that installed dongles consumes power even when the car is not in use. This is also true for dongles with a power-saving mechanism.

Among all the devices that have been presented in the present document, OBDLink seems to offer the characteristics that are the most compatible with MODALES. There are two reasons that prevented us to invest more time into the Freematics dongles. These devices are less shipped as an out-of-the-box solutions but gives developers the possibility to develop their own customized firmware for the device. This is not only going beyond the scope of the project but would also affect the CE-label of the device, that would have to be renewed for the firmware that we would provide with the dongle. This is a step that is not foreseen in the project.

As a consequence, and based on the previous findings and the pre-selection of the OBDLink dongles, the following specification should be the minimum requirement for the dongle used during the experimental phase of the project:

- OBD II male connector (J1962M) for light vehicles
- Supports all OBD-II protocols (including EOBD) and J1939
- Interface: Bluetooth
    - Physical pairing button
    - At least 128-bit data encryption
    - Minimum Class 2 Bluetooth v3.0 transmission
    - Profiles: SPP, iAP2
    - Support for iOS and Android
- Standby current < 2 mA
- Environmental working conditions -20º to 55º C at a humidity of 10 to 85% (non-condensing)
- 100 PIDs/second
- Certifications
    - RoHS
    - REACH
    - CE (ETSI EN 300 328 V1.8.1 (2012-06))
    - E-Mark ECE R10
    - EN 60950-1
- AT and ST command set
- Genuine products that can prove the source of the OBD interface chip

4. Testing and evaluation of relevant PIDs in cars

4.1. Performance indicators

The following categories of performance indicators were tested on real cars to analyse the availability of standardised PIDs for different cars:

- The ratio of available PIDs vs the total number of standardised PIDs
- Dependency of available PIDs in relation to the age of the car
- The number of cars that support the PIDs identified as emission-specific (Table 1)
- The sampling frequency of requests
- The average of single and multiple requests, as well as the standard deviation
- The dependency of the sampling frequency on the age of the car

Trucks and J1939 based protocols were not tested.

4.2. Test setup

The experiment was done using an OBDlink MX+ dongle connected via Bluetooth to a Linux laptop. The test was executed with a custom Python program that recorded the following parameters:

- VIN
- Interface Protocol
- Manual data if no VIN was read:
    - Brand
    - Model
    - Model-Year
- Query times for 10 queries of one PID (Vehicle Speed SID 01 PID 0D)
- Query time for 10 queries of a sequence of 5 available PIDs

23 cars participated in the tests, of which 13 were diesel vehicles, 9 petrol vehicles and one electric car with a petrol-based range extender. All cars were manufactured between 2002 and 2020. The set of cars tested was a random selection of cars of colleagues of the involved organisations.

4.3. Test results

It was expected that vehicles without the CAN interface available for OBD-II respond to single PID queries 10-50 times slower, however, it proved to be only 7 times slower. For the cars tested, it seems that older CAN-based cars seem to respond faster for single PID requests, but for multiple PID requests, as well as for the standard deviation, no dependency was identified.

The Digital Annexe of the 2019 SAE J1979 standard lists PIDs up to A9 with the highest supported PID of the cars tested being A6. As one can see in Table 5, the higher the number of supported PIDs in the range of 01-C0, the newer the car is. Without claiming full accuracy, newer cars from 2018 support PIDs in the >40% range, cars between 2007-2018 support PIDs in the 10%-25% range, and everything older than 2007 supports PIDs in the <10% range.

Table 5: Raw statistics of tested cars

Registration Year	Brand	Model	Fuel	Protocol	single PID avg.	multiple PID avg.	multiple PID stdev.	supported PID 01-A6	supported PID						
					ms	ms	ms	%	01-20	21-40	41 60	61- 80	81-A0	A1-B0	B1-C0
2020	Ford	Kuga	Diesel	ISO 15765-4 CAN 11 bit ID, 500 kBaud	24.7	25,4	14,7	38.9	🟩	🟩	🟩	🟩	🟩	🟩	
2019	Renault	Master	Diesel	ISO 15765-4 CAN 11 bit ID, 500 kBaud	25.0	41,7	19,1	22.2	🟩	🟩	🟩	🟩	🟩		
2018	Renault	Kadjar	Diesel	ISO 15765-4 CAN 11 bit ID, 500 kBaud	29.6	36,1	18,9	46,1	🟩	🟩	🟩	🟩	🟩	🟩	
2018	Peugeot	308	Diesel	ISO 15765-4 CAN 11 bit ID, 500 kBaud	15.9	26,5	15,6	24,0	🟩	🟩	🟩	🟩	🟩		
2018	Peugeot	5008	Diesel	ISO 15765-4 CAN 11 bit ID, 500 kBaud	15.3	26,0	15,2	24,0	🟩	🟩	🟩	🟩	🟩		
2018	Dacia	Duster	Diesel	ISO 15765-4 CAN 11 bit ID, 500 kBaud	34.4	43.7	16.8	22.3	🟩	🟩	🟩	🟩	🟩		
2018	Suzuki	Vitara	Petrol	ISO 15765-4 CAN 11 bit ID, 500 kBaud	20.9	54.6	63.3	19.9	🟩	🟩	🟩				
2017	Citroen	C3	Petrol	ISO 15765-4 CAN 11 bit ID, 500 kBaud	12.4	28,1	24,4	23.4	🟩	🟩	🟩	🟩			
2016	Suzuki	Vitara	Diesel	ISO 15765-4 CAN 11 bit ID, 500 kBaud	32.8	37.5	21.2	19.3	🟩	🟩	🟩	🟩			
2015	BMW	i3	electric[2]	ISO 15765-4 CAN 11 bit ID, 500 kBaud	35.9	40.6	20	23.5	🟩	🟩	🟩				
2015	Toyota	Yaris	Petrol	ISO 15765-4 CAN 11 bit ID, 500 kBaud	29.7	31.2	12.7	22.3	🟩	🟩	🟩				
2013	Citroen	C4 Grand Picasso	Diesel	ISO 15765-4 CAN 11 bit ID, 500 kBaud	16.0	32,8	24,8	13.2	🟩	🟩	🟩				
2012	Ford	Focus	Diesel	ISO 15765-4 CAN 11 bit ID, 500 kBaud	23.4	39.9	16.7	21.7	🟩	🟩	🟩	🟩			
2011	VW	Passat	Diesel	ISO 15765-4 CAN 11 bit ID, 500 kBaud	16.8	25,6	14,0	18.6	🟩	🟩	🟩				
2011	Fiat	Qubo	Diesel	ISO 15765-4 CAN 29 bit ID, 500 kBaud	32.8	46.9	12.8	11.4	🟩	🟩	🟩				
2007	Ford	Transit	Diesel	ISO 15765-4 CAN 11 bit ID, 500 kBaud	25.0	31.2	9.0	14.5	🟩	🟩	🟩				
2007	Hyundai	i30	Petrol	ISO 15765-4 CAN 11 bit ID, 500 kBaud	32.8	.53.6	20.2	17.5	🟩	🟩	🟩				
2007	Opel	Corsa	Petrol	ISO 15765-4 CAN 11 bit ID, 500 kBaud	34.4	48.8	16.5	20.8	🟩	🟩	🟩				
2007	Skoda	Fabia	Diesel	ISO 9141-2 5 Baud init, 10.4 kBaud	134.3	44.0	67.9	7.2	🟩	🟩					
2005	Renault	Megane CC	Petrol	ISO 14230-4 KWP fast Init 10.4 kBaud	130.8	44.4	69.8	10.2	🟩	🟩					
2004	Honda	CRV	Petrol	ISO 9141-2 5 Baud init, 10.4 kBaud	123.4	111.1	69.2	10.2	🟩	🟩					
2002	Seat	Ibiza	Petrol	ISO 9141-2 5 Baud init, 10.4 kBaud	157.8	192.0	50.5	10.8	🟩	🟩					
2002	Toyota	Yaris	Petrol	ISO 9141-2 5 Baud init, 10.4 kBaud	193.7	239.0	72.8	10.8	🟩	🟩					

The consequence for the availability of data, that we initially considered relevant for the project (Table 1) is shown in Table 6. All PIDs with available in at least in 65% of the cars are indicated in bold. These PIDs are additionally summarised in Table 7. If compared with fuel, petrol cars support far less of the relevant PIDs. Only PIDs for throttle position, vehicle speed, engine RPM, and engine coolant temperature are supported by at least 65% of the diesel-based cars and by at least 65% of the petrol based cars (indicated in the table in bold).

This might mean that we focus only on the parameters of Table 7 in our further investigation or that we focus only on cars that were introduced into the market 2018 or 2019 onwards. Unfortunately, we only expect changes in emission behaviour with change in driving style for older cars. For most recent cars little to no differences can be expected to be detected in the emissions because all Euro

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[2] electric car with range extender (petrol)

VI are sufficiently clean for detecting no changes in the emission behaviour with a change in the driving style.

Table 6: Availability of relevant OBD services in tested cars (13 Diesel, 9 Petrol, 1 Electric)

	Description	SID (hex)	PID (hex)	#Cars Diesel	#Cars Petrol	#Cars electric	#Cars Total
VIN	**Vehicle Identification Number (VIN)**	**9**	**02**	**11**	**4**	**1**	**16**
Gear	Transmission Actual Gear	1	A4	0	0	0	0
Gas pedal	**Accelerator pedal position D**	**1**	**49**	**11**	**3**	**1**	**15**
	Accelerator pedal position E	**1**	**4A**	**11**	**3**	**1**	**15**
	Accelerator pedal position F	1	4B	0	0	0	0
	Relative accelerator pedal position	1	5A	0	0	0	0
Throttle	**Throttle position**	**1**	**11**	**9**	**9**	**1**	**19**
	Absolute throttle position B	1	47	0	4	1	5
	Absolute throttle position C	1	48	0	0	0	0
	Throttle Position G	1	8D	0	0	0	0
	Relative throttle position	1	45	5	5	1	11
Speed	**Vehicle Speed**	**1**	**0D**	**13**	**9**	**1**	**23**
RPM	**Engine RPM**	**1**	**0C**	**13**	**9**	**1**	**23**
Torque	Driver's Demand Engine - Percent Torque	1	61	2	0	0	2
	Actual Engine - Percent Torque	1	62	2	0	0	2
Fuel Consumption	Engine Fuel Rate	1	5E	2	0	0	2
	Engine Fuel Rate	1	9D	2	0	0	2
Mass Air Flow	**Mass Air Flow Sensor (MAF) Air Flow Rate**	**1**	**10**	**13**	**3**	**0**	**16**
	Mass Air Flow Sensor	1	66	1	0	0	1
Air Pressure	**Absolute Barometric Pressure**	**1**	**33**	**12**	**4**	**1**	**17**
Temperature	Ambient Air Temperature	1	46	9	2	1	12
	Intake Air Temperature Sensor	1	68	2	0	0	2
	Engine Coolant temperature	**1**	**05**	**13**	**9**	**1**	**23**
	Catalyst Temperature: Bank 1, Sensor 1	1	3C	6	3	1	10
	Catalyst Temperature: Bank 1, Sensor 2	1	3D	0	0	0	0
	Catalyst Temperature: Bank 2, Sensor 1	1	3E	4	1	1	2
	Catalyst Temperature: Bank 1, Sensor 2	1	3F	0	0	0	0
NOx	NOx Sensor	1	83	1	0	0	1
	NOx Sensor Corrected Data	1	A1	1	0	0	1
Diesel particulate filter (DPF)	Particulate Filter Bank 1	1	7A	4	-	-	4
	Particulate Filter Bank 1	1	7B	0	-	-	0
	Particulate Filter Temperature	1	7C	1	-	-	1

Table 7: Relevant OBD services in tested cars that are available in at least 65% of the cars

	Description	SID (hex)	PID (hex)	#Cars Diesel	#Cars Petrol	#Cars electric	#Cars Total
VIN	Vehicle Identification Number (VIN)	9	02	11	4	1	16
Gas pedal	Accelerator pedal position D	1	49	11	3	1	15
	Accelerator pedal position E	1	4A	11	3	1	15
Throttle	**Throttle position**	**1**	**11**	**9**	**9**	**1**	**19**
Speed	**Vehicle Speed**	**1**	**0D**	**13**	**9**	**1**	**23**
RPM	**Engine RPM**	**1**	**0C**	**13**	**9**	**1**	**23**
Mass Air Flow	Mass Air Flow Sensor (MAF) Air Flow Rate	1	10	13	3	0	16
Air Pressure	Absolute Barometric Pressure	1	33	12	4	1	17
Temperature	**Engine Coolant temperature**	**1**	**05**	**13**	**9**	**1**	**23**

5. Sampling rate and data requirements

MODALES develops simulation and mathematical models to estimate the vehicle emissions from the powertrain, brakes and tyres, as a result of the change in driving behaviour. These models are calibrated by the real-world or in-lab measurements collected in MODALES Tasks 3.1 (Real powertrain emission methodology and measurement), 3.2 (Brakes emission methodology and measurement) and 3.3 (Tyre emission methodology and measurement). All the emission models are set up based on professional software, and their details (e.g., specifications, calibration and validation), are described in MODALES Deliverable 3.2 “Correlation of user behaviour variability with emissions” (under preparation at the time of writing and due later in 2021). In this section, we describe the sampling rates and requirements of the real data as well as the outputs from the models.

5.1. Sampling frequencies for powertrain emission modelling

5.1.1. GT-SUITE vehicle model

The sketch of the GT-SUITE [11] vehicle model used in the MODALES project is shown in Figure 2. The vehicle model mainly includes a driver module, a target speed module, ambient condition modules (e.g., road conditions and weather conditions) and a powertrain module (including control units, an internal combustion engine, transmission systems, and a cabin). The internal combustion engine module is based on the engine bench test maps, such as Friction Mean Effective Pressure (FMEP) maps, mechanical torque output maps, emission maps and brake-specific emission maps. When the driver uses the acceleration and deceleration pedals to reach the target speed, the control units force the internal combustion engine to operate under specific conditions to meet the power requirements. Ambient conditions include road gradients, road curvatures, wind speed, wind direction and humidity. The cabin and transmission systems are the intermediary of the internal combustion engine and the ambient. Ambient conditions will significantly affect the internal combustion engine operation conditions as well as the driver actions. The details of the input parameters of this GT-SUITE vehicle model are shown in Table 8. These parameters will influence the energy consumption by aerodynamic drag force, rolling resistance force, and energy consumption caused by the road gradients. Aerodynamic resistance in the simulation model is based on the user-defined parameters (e.g., the front area, aerodynamic drag coefficient). To ensure the accuracy of the simulation results, the parameters of road conditions (gradients and curvatures) during the actual driving should be collected at 10-metre intervals.

Table 9 shows the outputs of the vehicle model.

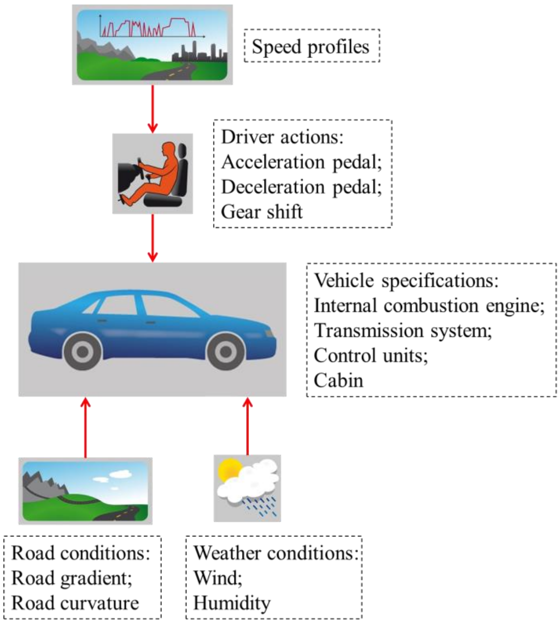

Figure 2: Sketch of the vehicle model

Table 8: Input parameters of the GT-SUITE vehicle model

Input parameters	Units	Frequency
Vehicle speed	km/h	1 Hz
Road gradient	%	1/(10m)
Road curvature	degree	1/(10m)
Wind speed	km/h	1 Hz
Wind direction	n.a.	1 Hz
Humidity	%	1 Hz

Table 9: Output parameters of the GT-SUITE vehicle model

Output parameters	Units	Frequency
Vehicle fuel consumption rates	kg/h	1 Hz
NO_x emission rates	mg/s	1 Hz
Accumulated fuel consumption	kg	n.a.
Accumulated NO_x emission	g	n.a.
Fuel economy	L/ 100 km	n.a.
NO_x emission factors	g/ km	n.a.
Engine speed	RPM	1 Hz
Engine power	kW	1 Hz
Tyre tractive forces	N	1 Hz
Brake torque	Nm	1 Hz

5.1.2. Mathematical powertrain emission model

The following equation shows the relationships between the instantaneous vehicle emission rates and KPIs of driving behaviours (to be covered in the forthcoming MODALES D3.2).

$$E_{NOx} = C_1v^6 + C_2v^5 + v^4(C_3 + C_4 + C_5sin\theta) + v^3(C_6sin\theta + C_7a + C_8) + v^2(C_9a^2 + C_{10}asin\theta + C_{11}(sin\theta)^2) + v(C_{12}a + C_{13}sin\theta + C_{14}) + C_0$$

Eq. 1

$\sim C_{14}$ are coefficients of the Equation. E_{NOx} is engine out NO_x emission rates; v is instantaneous vehicle speed; a is instantaneous vehicle acceleration; θ is road gradient.

In this equation, driving behaviours include the instantaneous vehicle speed and acceleration, and the data frequency is 1Hz.

The build of the mathematical emission model is based on the simulation results of the GT-SUITE vehicle model. Firstly, the relationships between the vehicle power and driving behaviours (e.g. vehicle speed and vehicle acceleration) are set up based on the following equation.

$$P(t) = \frac{1}{3600\eta_d}\, v(t) \left\{\frac{\rho}{25.92} C_D C_h A_f v(t)^2 \ + g\ MC_R + g\ M\ \sin\theta + (1+\lambda)\ Ma\right\}$$

Eq. 2

$P(t)$ is the vehicle power; η_d is the mechanical efficiency; ρ is the air density; $v(t)$ is the instantaneous vehicle speed; A_f is the front area of the vehicle; C_DC_H is the aerodynamic drag coefficient; g is the gravitational constant; C_R is the rolling resistant; λ is the rotational inertia; M is the vehicle mass; θ is the road grade; $a(t)$ is the instantaneous vehicle speed.

Then, the equation between vehicle power and engine-out emission rates is created based on the simulation results using a specific diesel passenger car. Finally, combinations of both equations, the relationships between engine-out emission rates and driving behaviours are obtained. When the vehicle is fully warmed up, the efficiency of the after-treatment systems is high and the pipe-out emission rates are quite low. The relationships between pipe out NO_x emission rates and driving behaviours will be significantly weakened, which means that there is not a strong correlation between emissions and driving behaviour due to the effect of after-treatment system. The input and output parameters of the NO_x mathematical equation model are shown in Tables 10 and 11.

$$E_{NOx} = f(P(t))$$

Eq. 3

Table 10: Input parameters of the mathematical emission model

Input parameters	Units	Frequency
Instantaneous Vehicle speed	km/h	1 Hz
Instantaneous vehicle acceleration	m/s^2	1 Hz
Road gradient	%	1/(10m)

Table 11: Output parameters of the mathematical emission model

Output parameters	Units	Frequency
NO_x emission rates	mg/s	1 Hz

The simulation and mathematical models for powertrain emission are compatible with the future potential data collection in WP6. The frequency of the output parameters in the emission models is referred to the specifications of the data collection equipment.

5.2. Sampling frequencies for brake emission modelling

5.2.1. Physical model for brake wear emissions

The brake physical model was built according to a brake system of a typical medium-sized car. This disc brake consists of a sliding calliper, two low-metallic pads, and a ventilated grey cast-iron rotor. The mass and wheel radius of this medium-sized passenger car is 1600 kg and 314 mm. Figure 3 shows an overview of physical model simulation for brake wear. The procedure starts with a pre-process in which the geometries are defined, the meshes are generated and test cycle is set. In the current study, the rotor inner, outer, and effective radiuses are 80, 139 and 113 mm, with a pad surface area is 5080 mm^2. The finite element simulation includes the disc brake components: rotor, pad friction material, backplates, piston, calliper, carrier and sliding pins. The input parameters, including initial and final velocities when braking, deceleration rate during braking, braking time, applied load and initial disc temperature are defined according to various brake events, as shown in Table 12.

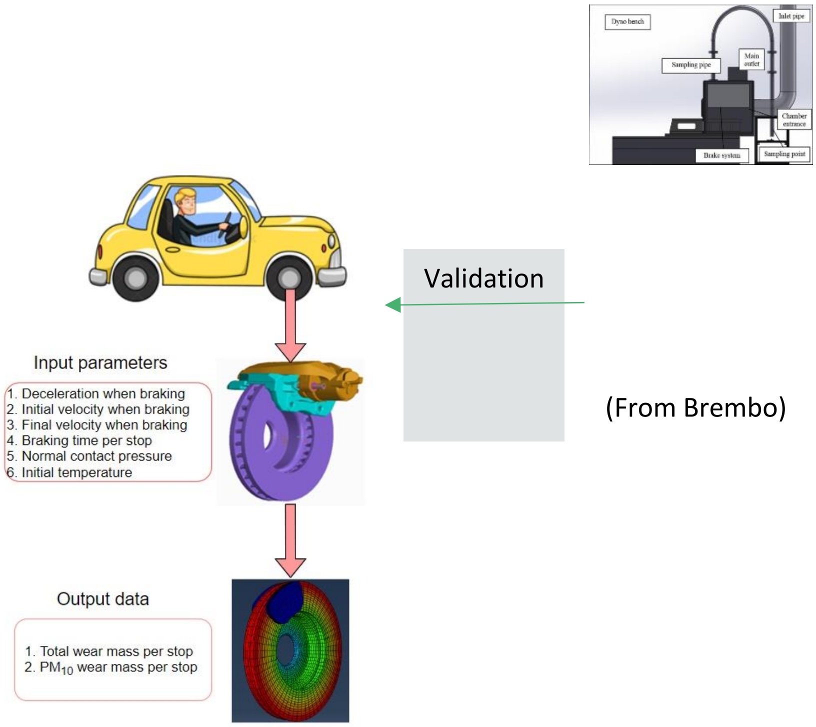

Figure 3: Overview of brake physical model

Table 12: Input parameters for brake physical model

Input data	Units	Frequency of data acquisition
Deceleration rate during braking	m/s^2	0.1 Hz
Initial velocity when braking	km/h	1 Hz
Final velocity when braking	km/h	1 Hz
Braking time per stop	s	1/stop
Normal contact pressure	MPa	0.1 Hz
Initial temperature for disc and pad	°C	1 Hz

Table 13: Output data for brake physical model

Input parameters	Units	Frequency of data acquisition
Pad wear depth	mm	1/stop
Disc wear depth	mm	1/stop
Pad wear mass per stop	mg	1/stop
Disc wear mass per stop	mg	1/stop
PM_{10} mass per stop (i.e., pad and disc wear mass)	mg	1/stop

The calliper can slide with respect to the grounded carrier on the sliding pins. The load consists of two steps: First, pressure is applied to the back of the piston and to the cylinder walls. Second, the pressure is kept, and a motion is applied to the rotor to simulate the rotation. The output of the finite element analysis is the contact pressure distribution of the pad-disc interface during braking. To simplify the wear routine, the rotor and friction material mesh is set to be hexahedral and the angular distance between nodes (Δθ) on the brake ring is set to be constant. The Abaqus ALE (Arbitrary Lagrangian Eulerian adaptive meshing) technique manages the node position update after every braking instance [7]. The output data and frequency of data acquisition are listed in Table 13.

5.2.2. Mathematical model for brake wear emissions

The calculation equation according to the classical Archard wear theory proposed by J. Archard is as follows [8]:

$$V_w = \frac{1}{3} K F_N L \qquad \text{Eq. 4}$$

V_w is the wear volume; F_N is the normal force of the contact surface; K is the specific wear rate related to material component; L is the relative sliding distance.

When braking, the work done against friction must be equal to the kinetic energy of the vehicle [9].

$$NkF_N L \cong \frac{1}{2} M(v_1^2 - v_2^2) \qquad \text{Eq. 5}$$

$$F_N L \cong \frac{1}{2} \frac{M(v_1^2 - v_2^2)}{Nk} \qquad \text{Eq. 6}$$

N is the number of brake assemblies of each vehicle; k is the friction coefficient; M is the vehicle mass; v_1 is velocity when the vehicle begins to brake; v_2 is velocity when the vehicle stops braking.

$V_w = K\frac{F_N L}{3} = \frac{KM}{6Nk}(v_1^2 - v_2^2)$	Eq. 7
$m = \rho V_w = K\frac{F_N \rho L}{3} = \frac{K\rho\varphi M}{6Nk}(v_1^2 - v_2^2)$	Eq. 8

In the physical model, brake pad and disc wear mass per stop can be obtained. In parallel, brake pad and disc wear mass can be calculated using our developed mathematical model. As a result, the physical and mathematical output data can be compared.

5.3. Sampling frequencies for tyre emission modelling

5.3.1. Physical model for tyre wear emissions

A commercial P205/55R16 tyre is considered for the numerical implementation of the proposed wear amount estimate, and an overview of a physical model of a tyre is shown in Figure 4. Tread rubber blocks are manufactured with carbon-black-filled polybutadiene and the outer radius R and the width are 316 and 205 mm. The frictional dynamic rolling analyses were performed with the ABAQUS/Explicit code [10]. Individual driving behaviours are implemented to require detailed input data and frequency of data acquisition when driving, as shown in Table 14. The frictional coefficient between the tyre and ground, known as the penalty parameter, was set to constant values, respectively, regardless of the driving mode. On the other hand, the remaining loading conditions are dependent on the driving mode.

Table 15 lists the output data and relative frequency of data acquisition.

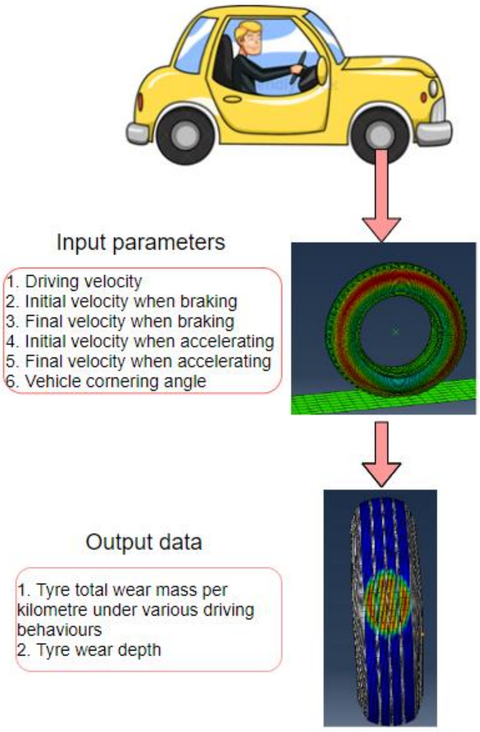

Figure 4: Overview of tyre physical model

Table 14: Input parameters for tyre physical model

Input parameters	Units	Frequency of data acquisition
Driving velocity	km/h	1 Hz
Initial velocity when braking	km/h	1 Hz
Final velocity when braking	km/h	1 Hz
Initial velocity when accelerating	km/h	1 Hz
Final velocity when accelerating	km/h	1 Hz
Acceleration rate	m/s^2	1 Hz
Vehicle cornering angle	°	1 Hz

Table 15: Output data for tyre physical model

Output data	Units	Frequency of data acquisition
Tyre wear depth	mm	1/km
Tyre wear mass per km	mg/km	1/km
Pressure distribution of tyre surface	MPa	1 Hz
Energy consumption per km	N m/km	1/km

5.3.2. Mathematical model for tyre wear emissions

According to the reported literature [12,13], the relation between the frictional power per unit contact area and the mass loss per unit covered area may be approximated by the following expression:

$$m_T = \varphi k_1 (\frac{P(t)}{\varphi NBL})^{k_2} BD \qquad \text{Eq. 9}$$

m_T is the mass loss; φ is the transverse reduction coefficient due to the tyre pattern; w is the frictional power per unit contact area; k_1 and k_2 are two constants that characterise the wear behaviour of the rubber compound at a given temperature and on a given abrasive surface; B is contact width between tyre and ground and D is the driven distance of vehicle; N is the number of tyre of the vehicle; L is the contact length between tyre and ground; P(t) is the energy consumption.

$$P(t) = \frac{1}{3600\eta_d}\, v(t) \left\{ \frac{\rho}{25.92} C_D C_h A_f v(t)^2 \; + \frac{g\ M\ C_r}{1000} [c_1 v(t) + c_2] + g\ M\ G(t) + (1+\lambda)\ M \frac{dv}{dt} \right\} \qquad \text{Eq. 10}$$

C_h is altitude; g is gravity; ρ is air density; G(t) is slope; M is vehicle weight; A_f is vehicle frontal area; C_D is drag; C_r is rolling resistance factor; c_1 and c_2 are rolling parameters; η_d is driveline efficiency; λ is Rotl masses.

The output parameters of the mathematical model for tyre wear emissions have the same sampling frequencies of data acquisition as that of the physical tyre emission model. In the physical model, tyre wear mass per kilometre can be obtained. The mathematical model can also output tyre wear mass per kilometre. In this model, this factor has been considered.

Most of the variables that are described above can be collected through OBD or via a smartphone. Only the ones related to tyre and the braking system cannot be guessed. The interested reader can refer to MODALES Deliverable 5.2 [2] for more information.

6. Recommendations for a broader use of OBD

6.1. Regulation

The European OBD regulation is part of the United Nations Global Technical Regulation No. 15 (GTR-15), Worldwide harmonised Light vehicles Test Procedures (WLTP), Amendment 6. It introduced Annex 11, covering provisions relating to On-Board Diagnostics (OBD), developed from the OBD procedure in Annex 11 of the 07 series of amendments to UN Regulation No. 83. The most important update was the introduction of the WLTC in place of NEDC. It is dated 18 January 2021. The latest update to this is Amendment 6/Appendix 1, which introduces Appendix 3 for the CoP (Conformity of Production) testing of OBD. It is also dated 18 January 2021.

In Amend. 6, Chapter 5.5 deals with Provisions for electronic system security, and is the only chapter in this regulation that specifically mentions “tampering”, in 5.5.1, by saying: “Any reprogrammable computer codes or operating parameters shall be resistant to tampering and afford a level of protection at least as good as the provisions in ISO 15031-7: 2013.” In addition, 5.5.2. states that “Computer-coded engine operating parameters shall not be changeable without the use of specialised tools and procedures (e.g., soldered or potted computer components or sealed (or soldered) enclosures).” Furthermore, in 5.5.4., the text states: “Manufacturers using programmable computer code systems shall deter unauthorised reprogramming. Manufacturers shall include enhanced tamper protection strategies and write-protect features requiring electronic access to an off-site computer maintained by the manufacturer. Methods giving an adequate level of tamper protection shall be approved by the responsible authority.”

Should any further modifications to increase the resistance of EOBD against tampering be developed and recommended, this piece of regulation, along with the ISO 15031-7: 2013 standard, are the vehicles to be used to implement these reforms.

6.2. EOBD

In the planning phase of MODALES, the general assumption was that both (a) lack of service and (b) deliberate tampering would increase tailpipe emissions, as both are likely to increase exhaust emissions and deteriorate the performance of EAT systems. Furthermore, the supposition was that the present EOBD system is designed to detect loss of performance, and when the tailpipe emissions increase beyond the set “OBD Threshold Limits” (OTL), the “Malfunction Indicator Light” (MIL) comes on, and one or more “Diagnostics Trouble Codes” (DTC) are stored in the system memory. This way the motorist is alerted that a critical malfunction exists, and the service provider that will eventually resolve the problem can use the DTCs to troubleshoot the system and find the root cause of the malfunction.

6.3. Lack of service

However, postulate (a) could not be supported with the results of our experiments from Task 3.4. The test results demonstrated that within normal service intervals, the excess emissions are quite negligible, and post-service emission levels in most cases were at the same level as before service, especially taking into account the accuracy of this type of measurement. See D3.1 for more details. Thus, the negligence of motorists regarding service must be quite severe before exhaust emissions are critically affected and could lead to the triggering of an event. It was also noted that the changes in fuel consumption due to service were somewhat ambiguous, with some cars reacting positively to the lowering of the consumption, others reacting in the opposite way, and some remaining more-or-less at the same level. However, changes in all cases were very small, and close to the level of the margin of error in this kind of chassis dynamometer tests. Therefore, the incentive for the motorist to properly maintain the vehicle's state-of-tune seems to be quite low.

Nevertheless, this statement was made on servicing focused only on the engine, yet mechanical items like binding brakes or weak shock absorbers can adversely affect the rolling resistance of the vehicle, which in turn increases energy and fuel consumption, with an expected upsurge also in tailpipe pollutants. However, within the scope of MODALES, this kind of testing was not performed, mainly due to the difficulty in finding suitable candidate vehicles. Still, the literature can give estimates for these increases, as seen in several reports published e.g., [6]) on the effect of road load setting on a dynamometer test, as binding brakes work just like setting a higher rolling resistance figure on the bench.

Furthermore, the literature review in MODALES D2.2 [1] revealed that even if the Emissions after Treatment System (EATS) performance deteriorates resulting in elevated emissions that violate OTL and lead to MIL activation and one or more DTC is duly generated, the vehicle owner/operator can use inexpensive hardware dongles and readily available software to turn off the MIL and clear the DTCs. This can be made e.g., just before a Periodic Technical Inspection (PTI), in the hope of passing it, especially if the offset is only the cost of a PTI, normally less than €100, should the vehicle fail, whereas repairing the actual faults can be much more costly. This being the case, with the functionalities of present EOBD, there are few prospects for expanding the use of EOBD to expose excess emissions due to lack of maintenance and compel the motorists to rectify the situation.

6.4. Tampering and detecting tampered vehicles

Regarding the effects of tampering and the means to detect that a vehicle has become a subject of tampering of the EATS, the presumption was that even quite serious actions like removal of the DPF, which will cause an increase in tailpipe particulate emissions by close to two orders of magnitude, are not necessarily detected in PTI, for example, due to the results of the common smoke opacity test not automatically correlating with PM or PN emissions rates.

Furthermore, in the literature (see MODALES D2.2, Chapter 4) there was evidence that the present EOBD system is not robust against actions that are used to circumvent the OBD system's ability to detect/report elevated emission levels due to tampering. The main reasons listed for this were that was no provision to permanently store DTCs, and no "readiness bits" implemented in EOBD that indicate whether sub-system monitoring has been recently completed with success. This permits the user to clear DTCs and turn off MIL repeatedly, without leaving a trace. Although the readiness test reveals that one or more monitoring functions have not completed their diagnostics cycle (usually, there is a time window or number of starts with the fault not detected to set the readiness bit), there is no way of sanctioning the condition, because it can be claimed to be a result of disconnecting the battery, which will lead to a similar status. However, it is well-known that sometimes PTI officers refuse to accept an OBD test if the main readiness bits are not set, and they advise the motorist to book a new test at a later time to allow all monitoring functions to properly complete their cycles.

Both these missing functionalities are implemented in US and Korean OBD systems. Furthermore, these systems also contain, a provision to check whether the ECU carries original or non-original software.

These three fundamental weaknesses make the EOBD system susceptible to various kinds of “attacks”, and, therefore, reinforcing the “shields” of the EOBD is necessary to prevent the manipulation of the system to allow tampered vehicles to operate without restrictions on torque (power), and in many cases even to pass a PTI with hardware/software that has been tampered with.

Regarding these necessary fortifications, the European project DIAS (Smart Adaptive Remote Diagnostic Antitampering Systems, Grant Agreement ID# 814951) has recently investigated the culture of tampering and what is offered and to which applications in its Deliverable D3.1: “The market of cheating devices and testing matrix with a prioritization for testing of vehicle tampering technique combinations” [17]. This deliverable reports a market assessment that was conducted to determine the extent of tampering in terms of size, appearance and involved players, and to reveal motivations for tampering and identify the different types of tampering offered. The exercise led to a test matrix of vehicle/tampering combinations that were expected to pose the largest environmental risk, and which should thus be tested in order to determine the current vulnerabilities and exploits of vehicles that need to be addressed by the new concept devised by the DIAS project.

Furthermore, in DIAS Deliverable 3.2: “Status quo of critical tampering techniques and proposal of new OBD monitoring functions required” [18], the tampering/vehicle combinations selected were subjected to various kinds of emissions tests to determine the working principles of tampering. Based on this effort, requirements were defined for measures that need to be developed to counteract existing tampering attempts by prevention and detection. Furthermore, detailed results of the test programme, such as descriptions of how tampering works, what vehicle signals are affected and how tampering can remain undetected are reported in a separate confidential report (DIAS D2.2: “End-user requirement & use case definition” [16]).

The tampering “solutions” that were evaluated showed mixed results, ranging from successful tampering to tampering that did not work at all. Furthermore, some forms of tampering were tested, where diagnostic trouble codes (DTC) were generated and stored either immediately or eventually, and the MIL came on, just as expected. However, the most successful tampering was able to deactivate reagent dosing of the SCR system, deactivate EGR valve actuation, allow the removal of critical EATS components such as a DPF, and allow the use of faulty components on the vehicle, while no diagnostic trouble codes were generated, no MIL came on and no power limitations were induced.

The report also acknowledged that most tampering solutions were made for vehicles that do not represent the latest stage of emission regulations, as it takes time to develop techniques that bypass or circumvent the control measures meant to detect tampering. Also, each generation of regulations has increased the number and performance level of the EATS components, as well as the number of anti-tampering efforts.

According to DIAS D3.2, based on the tampering techniques observed and vulnerabilities exploited, several general requirements were defined to be used as guidelines for the development of new functions for the detection or prevention of tampering and which would ensure that the OBD would detect faulty components of the Environmental Protection System (EPS).

For the first level, the general requirements listed were:

- Assuring the data integrity of the signals from sensors and actuators that take part in the control of the EPS and the on-board diagnostics system. This entails both digital signals, where the option is to detect or prevent the injection of false signals by authenticating digital signals or ensuring the integrity of analogue and digital signals by using advanced data rationality checks;

- Assuring the data integrity of the Electronic Control Unit (ECU), where the preferred option is to detect or prevent the unauthorised flashing of ECUs by advanced security features;
- Detection or prevention of the malicious erasing of the fault code memory of the on-board diagnostics system.

Furthermore, DIAS D3.2 suggested that options to fulfil the requirements to detect or prevent tampering, especially taking into account user requirements should be investigated further. It also stated that since current OBD does not foresee a functionality to detect and report tampering, it is advised to consider developing continuous tampering diagnostics with tampering probability monitoring and reporting.

It was also recommended to consider tampering checks for PTIs. The tampering diagnostics could assist the enforcement of the proper functioning of the EPS at a regular PTI, as well as in roadside inspections or for the monitoring of tampering in the fleet through a cloud service. This feature could be part of an integrated environmental performance monitoring system, which not only monitors tampering but also performs other monitoring functions, such as monitoring the emissions performance (On-board monitoring, OBM) and fuel consumption (On-board Fuel and/or Energy Consumption Monitoring, OBFCM), a feature implemented in all new passenger vehicles since 01/01/2021.

Additionally, DIAS D3.2 recommended continuing to monitor market developments for the introduction of new tampering techniques, and to continue to investigate how current security features for ECUs are bypassed. DIAS has arranged a Hackathon event for this purpose.

Because of this very in-depth and thorough investigation being carried out by DIAS, it was deemed unnecessary for MODALES to perform similar exercises to address the question of how to detect vehicles that have been tampered with using the most cost-efficient and powerful methods. Instead, MODALES chose to echo the findings and suggestions of DIAS to date and will report on these during the remaining duration of the project.

The MODALES solution, which will be developed in Task 4.2 of the project, is based on the analysis of OBD and smartphone data while driving. Tabulation of raw data (e.g., speed vs REVs) as well as calculated values (e.g., acceleration) will be evaluated, taking into account the vehicle type and the manufacturer characteristics, and conclusions will be drawn about the potential tampering of the vehicle. As far as the maintenance is concerned, all warnings and fault messages will be stored in an on-board device. This information will be available to the vehicle owner (through a dashboard) and to the periodic inspection centre technician who will perform the vehicle check.

7. Conclusion

The objective of this derivable was to propose recommendations for a broader use of OBD. This objective has been achieved on several levels:

- We analysed the OBD and J1939 standards with regard to service IDs that could be relevant for the identification of driver behaviour and their negative impact on vehicles.
- In addition, we needed to identify and select dongles that could be used in a field test to access these service IDs. To do so, we carried out an analysis of the most popular dongles available on the market, identified the properties of these dongles, decided which properties we would need in the future (WP6) and, on this basis, selected the brand and models of dongles we thought would be most useful for the project.
- With the selected dongles, we developed a software to record the availability of OBD services and used it on a small number of cars of various ages and fuels. Already at this level, we realised that the support of OBD services strongly depends on the age of the car and that from the initial list of relevant services, only very few are widely supported in cars. In fact, only throttle position, vehicle speed, engine speed and engine coolant temperature are supported by almost 100% of the cars tested. A consequence could be that we only focus on these parameters in our next investigations or that we only focus on cars that were introduced to the market from 2018 or 2019 onwards, as they support a broader set of services.
- In addition to the OBD-specific approach, we presented a general car model that provides a vehicle model consisting mainly of a driver module, a target speed module, ambient condition modules (e.g., road and weather conditions) and a powertrain module (including control units, internal combustion engine, transmission systems and passenger compartment). This model can be used as a reference to understand the variables that are connected to driving behaviour and the sampling rate requirements (which all have an effect on the data collection processes).
- The implications of these results were discussed in a dedicated section on recommendation for wider use of OBD, which also addressed regulatory aspects and the possibility of identifying vehicle tampering.

By modelling certain aspects of cars, as well as analysis of the availability of relevant services in real-world cars, this work package lays down the foundation for later stages of the project. In particular, the discrepancy of requested and available information that is accessible via OBD will influence the model that describes the car and the driver behaviour, as well as the quality of the outcome of a certain analysis.

8. References

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