Adapting driver behaviour for lower emissions

MODALES D1.5: Publishable Final Report

WORK PACKAGE WP1	Project Management
TASKS 1.1 & 1.2	Project Coordination and Administration; Technical Coordination
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DISSEMINATION LEVEL	Public (PU)
STATUS	Final submitted to EC. Subject to European Commission approval
DUE DATE	31/05/2023
DOCUMENT DATE	30/11/2023
VERSION NUMBER	1.1

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 815189.

Quality Control

	Name	Organisation	Date
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Submitted by (Project Coordinator):	Andrew Winder	ERTICO	24/11/2023

Revision and history chart

Version	Date	Main author	Summary of changes
0.1	29/05/2023	A. Winder	Draft outline
0.2	30/10/2023	A. Winder	Final draft
1.0	24/11/2023	A. Winder	Final submitted version
1.1	30/11/2023	A. Winder	Version for website with minor edits

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This document is issued within the framework of and for the purpose of the MODALES project. This project has received funding from the European Union's Horizon 2020 Framework Programme, through the Innovation and Networks Executive Agency (CINEA) under the powers delegated by the European Commission and under Grant Agreement No. 815189. Opinions expressed and arguments employed herein do not necessarily reflect the official views of the European Commission or CINEA. Neither the European Commission nor the MODALES partners bear any responsibility for any use that may be made of the information contained herein. This document and its content are the property of the MODALES Consortium. All rights relevant to this document are determined by the applicable laws. Access to this document does not grant any right or license to the document or its contents. MODALES partners may use this document in conformity with the MODALES Consortium Grant Agreement provisions.

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Glossary, acronyms and abbreviations

Glossary of terms

Term	Description
Eco-driving	The practice of driving in such a way as to minimise fuel consumption and the emission of carbon dioxide (CO_2)
Low-emission driving	The practice of driving in such a way as to minimise the emission of pollutant emissions (such as CO, NO_X, PM and PN)
MODALES	This EU Horizon 2020 project: "Modify Drivers' behaviour to Adapt for Lower Emissions" (2019-2022, http://modales-project.eu)
Phase 1	Baseline phase of the MODALES trials, before the training, in which drivers drove with the app in data collection mode only
Phase 2	Treatment phase of the MODALES trials, after the driver had viewed the training video and is using the app in full mode (giving on-trip and post-trip feedback)

MODALES partners

Abbreviation	Full partner name
ACASA	Automòbil Club Assistència SA *(operating company of RACC Mobility Club – Real Automòbil Club de Catalunya / Royal Automobile Club of Catalonia)*
BREMBO	Freni Brembo SpA
BRIDG	Bridgestone Europe NV/SA
CEREMA	Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement
CERTH	Centre for Research and Technology Hellas / Ethniko Kentro Erevnas kai Technologikis Anaptyxis
DYNN	Dynnoteq Ltd
ERTICO	ERTICO – ITS Europe *(MODALES project coordinator)*
FIA	Fédération Internationale de l'Automobile
IRU	International Road Transport Union
LEEDS	University of Leeds
LIST	Luxembourg Institute of Science and Technology
MICH	Manufacture Française des Pneumatiques Michelin
NST	Nanjing Sample Technology
OKAN	Istanbul Okan University / İstanbul Okan Üniversitesi
PROV	Proventia Oy
SEU	Southeast University (Nanjing, China)
SPARK	Spark Legal Network (EU) BVBA
VTT	Technical Research Centre of Finland Ltd / Teknologian Tutkimuskeskus VTT Oy

modales

List of general abbreviations and acronyms

Abbreviation	Meaning
ACCT	Ammonia Creation and Conversion Technology
AI	Artificial Intelligence
API	Application Programming Interface
ARTEMIS Urban	Urban variant of the real-world driving cycles developed by ARTEMIS, a European project on the accuracy of emissions tests
CAN	Controller Area Network
CINEA	European Climate, Infrastructure and Environment Executive Agency/
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DPF	Diesel Particulate Filter
DTC	Diagnostic Trouble Codes
EATS	Engine (or Exhaust) After Treatment System
EC	European Commission
ECU	Electronic Control Unit
EGT	Exhaust Gas Temperature
EHC	Electrically Heated Catalyst
EOBD	European On-Board Diagnostics
EPS	Environmental Protection System
EU	European Union
g/km	Grams per kilometre
GPS	Global Positioning System
HC	Hydrocarbons
HDV	Heavy Duty Vehicle
HMI	Human-Machine Interface
I/M	Inspection and Maintenance
ICE	Internal Combustion Engine
IoT	Internet of Things
IS	Innovation Solution
ITS	Intelligent Transport Systems
KPI	Key Performance Indicator
l/km	Litres per kilometre
LDV	Light Duty Vehicle
LNT	Lean NO_X Trap
MIL	Malfunction Indicator Light
NEDC	New European Driving Cycle
NO_X	Nitrogen Oxides
NOxBUSTER®	Retrofit emission control system (DPF and SCR) from Proventia

Abbreviation	Meaning
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*
OEM	Original Equipment Manufacturer
OS	Operating System
PEMS	Portable Emissions Measurement System
PGN	Parameter Group Number (J1939)
PID	Parameter ID (OBD II)
PM	Particulate matter
PM_1	Particulate Matter 1 micrometre or less in diameter
PM_{10}	Particulate Matter 10 micrometres or less in diameter
$PM_{2.5}$	Particulate Matter 2.5 micrometres or less in diameter
PN	Particle number
PN_1	Particle Number 1 micrometre or less in diameter
PN_{10}	Particle Number 10 micrometres or less in diameter
$PN_{2.5}$	Particle Number 2.5 micrometres or less in diameter
PSD	Particle size distribution
PTI	Periodic Technical Inspection
RDE	Real Driving Emissions
RPA	Relative Positive Acceleration
RPM	Revolutions Per Minute
RQ	Research Question
SCR	Selective Catalytic Reduction
SUS	System Usability Scale
TS	Technology Solution
URL	Uniform Resource Locator
VIN	Vehicle Identification Number
WHVC	World Harmonized Vehicle Cycle
WLTC	Worldwide harmonized Light vehicles Test Cycles
WLTP	Worldwide harmonised Light vehicles Test Procedures
WLTP-brake	Worldwide Harmonized Light-duty Vehicles Test Procedure for brake devices
WP	Work Package (in MODALES)

Executive Summary

Context and overall objectives of MODALES

MODALES worked to reduce air pollution from road vehicles by encouraging the adoption of low-emission driving behaviour and proper maintenance choice, improving the effectiveness of on-board diagnostics (OBD) devices and technical inspections to detect tampering, analysing the effectiveness of retrofits for different types of diesel vehicles to reduce NOx emissions, and developing training and awareness materials.

The impact of road traffic on local air quality is a major policy concern. Although zero tailpipe emission technologies will make a major contribution towards solving the problem in the longer term, fleet renewal takes time and current road traffic is will still be dominated by internal combustion fleets for years to come. Furthermore, particulate emissions from brakes and tyres are an issue even for electric vehicles. On-road emissions can also be significantly different from laboratory measurements. Real-world emissions can be affected by many factors including vehicle characteristics, ambient temperature, traffic, road layout and driver behaviour. Driver behaviour is regarded as the single biggest determinant of the emissions of a vehicle. MODALES worked to advance the understanding of the co-variability of user behaviour and vehicle emissions and to improve user behaviour via training, assistance and awareness.

The project's objectives were to:

- Understand and correlate driving behaviour with real powertrain (exhaust) emissions and emissions from brakes and tyres, with a focus on Internal Combustion Engine cars and commercial vehicles.
- Promote low-emission oriented driving through awareness, training and a real time assistant (smartphone app).
- Assess the real effectiveness of OBD and technical inspections.
- Investigate the legal situation of tampering in Europe.
- Assess the potential impact of retrofits.

Work performed and main results

The project began by defining low-emission factors (WP2), in which over 250 papers and reports were analysed to define various driving behaviours. It produced recommendations and guidelines for real driving data to be collected in MODALES. A task on OBD inspection and maintenance (I/M) requirements studied I/M practices and the effectiveness of I/M to detect high emitting vehicles. It reviewed OBD protocols and investigated "inspection databases" in some European countries, in order to identify key issues in maintenance behaviour. Data was collected from installations of retrofit systems in buses. A task on low emission driving requirements carried out a comparative analysis of low-emission driving and eco-driving, taking into account safety criteria. It transferred scientific results into best practices for low-emission training and education. Data collection and analysis was carried out on legal issues on tampering in 14 countries in Europe.

Work on the impact of user behaviours (WP3) used a Portable Emission Measurement System (PEMS) on a 30 km route in Finland, with a pool of 15 drivers in 6 cars, to measure real powertrain emissions. A brake dynamometer test was set up and was used to perform emission tests on a reference vehicle with two different testing cycles. Tyre wear (mass-loss) measurement campaigns were also carried out, with data collection from taxi fleets in Italy and Greece.

In WP4 on Effectiveness of Inspections and Depollution Systems, the project benchmarked and selected the OBD dongles to be used during the user trials of the smartphone app. Periodic inspections and other anti-tampering solutions involved a market review on devices for CAN Bus data sniffing. A retrofit demonstration for a light commercial vehicle was done, with a mechanical installation, emission testing and integration to vehicle electronics. The system was tested to meet emission reduction requirements and results were satisfactory.

The project developed guidelines and tools for low-emission training (WP5) including a scoring algorithm using AI techniques. Guidelines for low-emission driving were proposed, functional specifications of the MODALES Smartphone app and a web dashboard were made. The app with a data collection module was produced in Android and iOS versions. Training videos for low-emission driving were developed and made available in eight languages, reflecting the needs of the trial sites.

In User Trials and Evaluation (WP6), an Evaluation Plan was created, followed by the recruitment of volunteer drivers for naturalistic trials of the training and app. The 170 drivers at seven European sites (in Finland, UK, Luxembourg, Spain, Italy, Greece and Turkey) drove in baseline mode for at least a month using the MODALES app coupled with an OBD dongle for data collection only. Then the drivers viewed the training video and updated the MODALES app so that it provided on-trip and post-trip feedback. They drove in this treatment phase using the app and the before and after data was compared for each user. The driving data from the dongle and app were transmitted to a server at MODALES partner LIST in Luxembourg and treated anonymously, with full respect for GDPR. Drivers also responded to different evaluation questionnaires. On-road trials also took place in Nanjing, China, but because of Chinese legal requirements, the MODALES app could not be used, only the training.

The trial results were largely positive, especially with respect to reducing brake emissions. With respect to exhaust emissions (NO_X), the overall median reduction across all seven European sites was 3.1% but this included users who did not register an improvement. Drivers in four of the cities registered average NO_X reductions between 0.8% and 4%, with the best performing drivers reducing their NOx by between 4.5% and 10.9% in these cities, showing the potential of this approach among those wiling to try to reduce their emissions. For brake wear emissions ($PM_{2.5}$ and PM_{10}, mg per stop), all sites recorded a substantial improvement with a median reduction of 19.7% for all sites, a median reduction of 37% at one site and the best performing drivers at all sites reducing their brake emissions by over 30% (and over 40% at two sites). For tyre wear (mg of tyre mass per km, before and after training), the average reduction was 3.3%, with the best performing drivers achieving over 10% reduction.

An impact assessment study was performed, which concluded that there is significant potential for savings through app-based solutions and training programmes that encourage more efficient driving. However, although these solutions are low-cost and relatively easy to implement, they may not be as effective as OEM embedded systems, which are typically more expensive but also more efficient.

Feedback questionnaires conducted among MODALES trial participants found that around a third of respondents used the app every time they drove during the trial period. Respondents generally considered that the MODALES app successfully encouraged behavioural changes in driving, with many respondents reporting a reduction in poor driving behaviour. However, some issues were raised with the app's design and functionality, and that a better performing and more stable version of the app (e.g. as a commercial application rather than a research project) would be welcomed by most respondents.

Overall, the research suggests that there is significant potential for reducing emissions in the transportation sector through a combination of anti-tampering measures, retrofit campaigns, and behaviour-related changes. However, the effectiveness of these measures will depend on a variety of factors, including the type of vehicle, the country in question, and the specific technology used. As such, a targeted and nuanced approach will be necessary to achieve meaningful reductions in emissions.

WP7 of MODALES produced annual dissemination plans and communication tools (e.g. website and brochure), media and messages, as well as technical dissemination mainly in the form of physical and online events and scientific papers (23 published). An Awareness Campaign (in 11 languages) was disseminated via the project website and the social media of motoring organisations in several European countries, as well as the driver training videos. WP1 carried out the Project Management, including Innovation, Ethics and Data Protection.

Progress beyond the state of the art

- Analysis of real effectiveness of OBD inspection and maintenance.
- Analysis of main parameters related to effective functioning of retrofit devices.
- Knowledge on legal situation regarding tampering in Europe.
- Data and analysis from PEMS measurement campaign near Helsinki, including variability among drivers and different cars.
- Brake dynamometer test data showing brakes dissipated 20% less energy in a driving cycle based on MODALES guidelines than in the case of the reference WLTP-Brake cycle.
- Validation of emission models for powertrain, brakes and tyres, allowing the ranking of driving behaviour KPIs. Sophisticated simulation models and mathematical equations for all three emission sources were well calibrated with various data (e.g. field measurements, in-lab tests, published literature)
- Low-emission training videos on project website aimed at car, light commercial and heavy commercial vehicle drivers.
- Provision of low-emission driving guidelines, awareness campaign and a driver support app, tested and validated in 7 countries with 170 drivers.

1. MODALES project context and objectives

The MODALES project ran from September 2019 to May 2023 and worked towards solutions to reduce air pollution from all types of on-road vehicles by encouraging the adoption of low-emission driving behaviour and proper maintenance choices. The focus was on Internal Combustion Engine (petrol and diesel) vehicles, providing practical "quick wins" for older vehicles. Although electric vehicles (EVs) were not within the scope of the project, several of the outcomes relating to user behaviour are also valid for EVs (or could be adapted for them).

MODALES pursued 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 a number of innovative and complementary solutions in four key areas (driver, retrofits, On-Board Diagnostics and periodic inspections) in order to reduce vehicle emissions from three main sources: powertrain (exhaust), brakes and tyres.

MODALES aimed to modify user (driver) behaviour via training including a driver assistance app supported by short training videos and an awareness campaign, in order to support effective air quality improvement plans and enforcement strategies to be developed by local and national authorities.

To achieve this goal, MODALES researched, developed and tested 13 Innovation Solutions, in order to substantially reduce vehicle emissions from the main sources given above, for passenger cars, light and heavy duty commercial vehicles (LDV, HDV) and Non-Road Mobile Machinery (NRMM). These are illustrated in Figure 1 below.

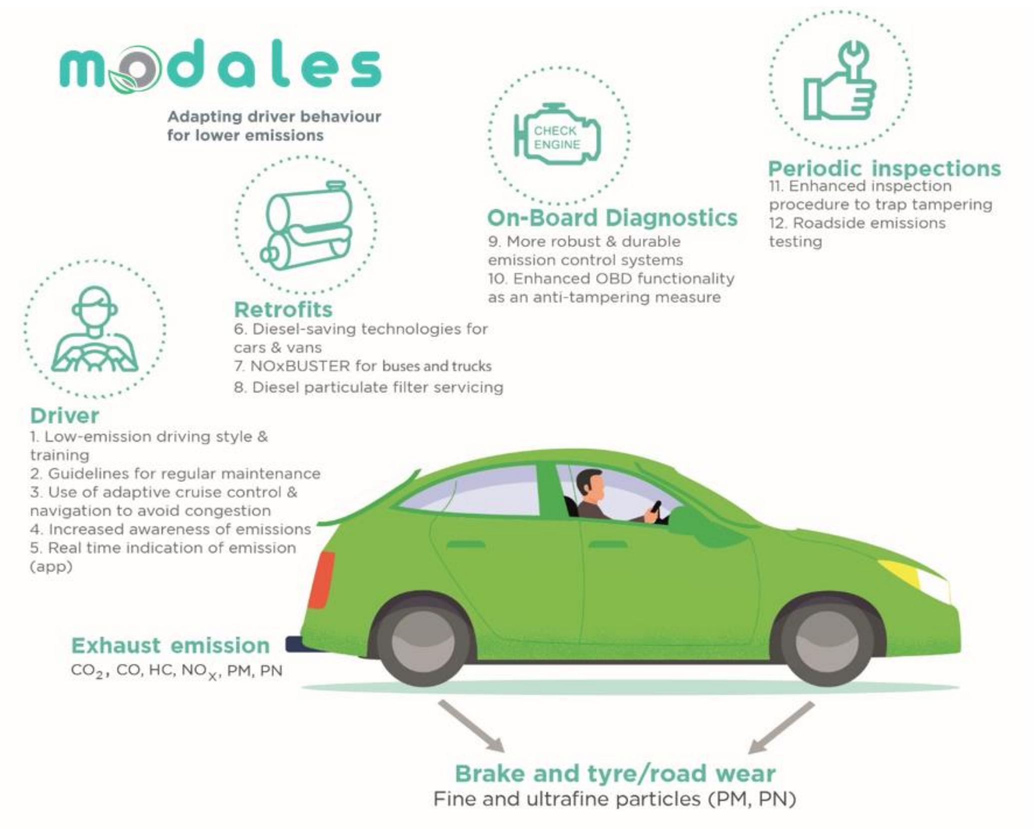

Figure 1: MODALES Innovation Solutions

As an International Cooperation project, MODALES included cooperation with China, with two International Partners in the city of Nanjing participating in many of the tasks.

The main activities of MODALES were:

- Measurement of real-world vehicle emissions and driving behaviour to produce accurate correlation 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 to 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 to help owners properly maintain their vehicles;
- Conducting large-scale user trials in Europe and China, supported by awareness campaigns, to enhance public engagement and help drivers better understand the impact of their driving and maintenance behaviours in all situations.

This Publishable Final Report gives a summary overview of the activities and key results of MODALES. For more detailed information, please refer to the individual public deliverables which are downloadable from the project's website: https://modales-project.eu/deliverables. In addition, technical and scientific papers to which the project contributed are available here: https://modales-project.eu/publications.

2. Main scientific and technical results

MODALES was organised around eight Work Packages (WP), each with a lead partner. These are as follows (see the "Glossary, acronyms and abbreviations" section at the beginning of this document for the partner acronyms):

- WP1: Project Management (WP leader: ERTICO)
- WP2: Defining Low-emission Factors (WP leader: LEEDS)
- WP3: Impact of User Behaviours (WP leader: VTT)
- WP4: Effectiveness of Inspections and Depollution Systems (WP leader: CERTH)
- WP5: Guidelines and Tools for Low-emission Driving (WP leader: LIST)
- WP6: User Trials and Evaluation (WP leader: ACASA)
- WP7: Awareness, Communication and Dissemination (WP leader: ERTICO)
- WP8: Ethics requirements (WP leader: ERTICO).

In order to simplify the project outcomes to readers who are not familiar with the project, this summary of results is organised around the four principal Innovation Areas depicted in Figure 1 (Driver, Retrofits, OBD and Periodic Inspections).

The technical Work Package(s) (WP2 to WP7) contributing to each Innovation Area are depicted in Table 1 below, in which relevant MODALES deliverables from each WP contributing to each Innovation Area are listed.

Table 1: Innovation areas and technical Work Packages in MODALES

Innovation Area: Work package	Driver	Retrofits	On-Board Diagnostics (OBD)	Periodic Inspections
WP2: Defining Low-emission Factors	**D2.1** (public)	**D2.2** (public)	**D2.2** (public)	**D2.2, D2.3** (public)
WP3: Impact of User Behaviours	**D3.1, D3.2** (public)			
WP4: Effectiveness of Inspections and Depollution Systems		**D4.3** (confidential)	**D4.1** (public)	**D4.2** (public)
WP5: Guidelines and Tools for Low-emission Driving	**D5.1, D5.3, D5.4** (public) **D5.2, D5.5** (confidential)			
WP6: User Trials and Evaluation	**D6.1** (confidential) **D6.2, D6.3, D6.4** (public)	**D6.1** (confidential)	**D6.1** (confidential)	
WP7: Awareness, Communication and Dissemination	**D7.4** (public)			

2.1. Innovation Area "Driver"

2.1.1. MODALES Innovation Solutions in the Driver Innovation Area

- Low-emission driving style and training
- Guidelines for regular maintenance
- Use of adaptive cruise control and navigation to avoid congestion
- Increased awareness of emissions
- Real-time indication of emissions (app)

2.1.2. Key "Driver" results from WP2: Defining Low-emission Factors

The first technical task of MODALES was to review the existing state of knowledge related to the project, and to thereby set out a set of recommendations for subsequent work packages, and specifically to guide the emission measurement campaigns planned for WP3 (Impact of user behaviours). The review conducted in WP2 (Deliverable D2.1) particularly focused on two key aspects: variability in driving behaviours and low emission driving requirements. The first element set out the project's understanding of the link between driving behaviours and emissions, and the second built on the understanding of existing low-emission driving programmes/projects to help set out what MODALES needed in order to realise the objective of low emission driving.

The literature review of driving behaviour variability was performed through a meta-analysis to identify typical driving patterns and practices. By reviewing and collating the findings from world-wide studies (e.g. Naturalistic Driving Studies, Field Operational Tests), was able to provide scientific evidence to the MODALES project on the characterisation of driver aggressiveness profiles, and to establish the link between vehicle emissions and driving behaviour based on both real world measurement and laboratory tests. The review demonstrated that we have a clear empirical understanding of many of the factors that influence different driving behaviours, ranging over characteristics of the driver (e.g. age, gender and experience), of the vehicle type (e.g. performance characteristics of the vehicle), and of the environmental conditions experienced (e.g. road type, gradient, curvature, surrounding landscape). As a consequence, and as demonstrated in the reviewed studies, driving behaviours vary from time to time, place to place and most importantly driver to driver, and the reviewed studies provide an understanding of the mechanisms underlying this variation.

Individual reviews were also conducted of the evidence of air pollution caused by exhaust emissions, brake wear and tyre wear. The emissions from exhaust gases have been widely studied, and various prediction models have been proposed and used for the development of policy interventions and traffic management measures aimed at improving air quality. The review showed, however, that there is a need for these predictive models to be validated with real monitoring data from real-world road tests under various conditions, in particular under different road environments, traffic characteristics, weather conditions, vehicle conditions, and most drivers with different driving styles (e.g. vehicle speed, acceleration and deceleration). On the brake wear side, the influence of different measurement methods was found to be the main source of the high variability in brake emission factors deduced from different studies. This leads to the implication that selection of the correct brake sequence for testing brake emissions is fundamental to the measurement of real-world emission factors.

As a general conclusion from these studies, any general guidelines for decreasing brake emissions should be based around encouraging a defensive and conservative driving style, characterised by the use of engine brake torque to limit the initial brake speed and the temperature of the braking system. On the tyre wear side, the review of the key factors related to tyre emissions indicated a wide variety of factors that influence the generation of tyre wear particles, and thus any future efforts at reducing this source would need to consider not only the characteristics of the tyre, but also the vehicle to which it is mounted, the manner in which the vehicle is operated and the type of pavement on which the vehicle is driven. It was found that very few studies had been carried out to simultaneously correlate driving behaviour variability with the three emission sources. It was also not clear from these studies how driving guidelines and practices should be developed to reduce vehicle emissions from all three sources in a consistent and optimised manner. This was one of the key challenges addressed in MODALES.

Some key conclusions on driving behaviour variability are:

- Private cars have the highest mean vehicle speed and speed variations compared to other types of vehicles, meanwhile they have the highest mean acceleration and deceleration in all speed ranges.
- During the daytime (especially in urban areas), vehicle speeds are lower than at night, which can cause a high exhaust emission factor compared to other time; meanwhile, speed deviations are quite high which indicates frequent deceleration and acceleration.
- Speed changes over different road types are quite different if training and eco-driving technologies are used.
- Vehicle speed distributions and acceleration distributions are different for various countries, which can be caused by the joint effects of weather, road characteristics, traffic conditions, driving behaviour, etc.
- Female drivers tend to drive slower than male drivers.
- Young drivers have a higher driving speed than older drivers; meanwhile old drivers drive gently with low speed deviations.
- Greater experience produces significantly smaller speed deviations; however, the effect of driving experience on mean vehicle speed is still in debate.

Some key conclusions for exhaust emissions are:

- Several emission monitoring approaches have been introduced, such as portable emission tests, remote sensors, and chassis dynamometer. In addition, various emission models that are widely used have been reviewed. The emission models can be divided into four categories: 1) Professional software-based models; 2) Regression models; 3) Inventory models; 4) Energy consumption-based models.
- Key driving behaviour related factors for exhaust emissions are: vehicle speed distribution; average speed; average driving speed without stops; % of distance in speed interval 50~70 km/h; acceleration distribution; average acceleration; % of time in acceleration; % of distance in acceleration; deceleration distribution; average deceleration; % of time in deceleration; % of distance in deceleration; frequency of stops; average stop durations; gear upshift speed; gear downshift speed; frequency of gear shift; average engine speed when shifting gear up.
- Key non-driving behaviour related factors for exhaust emissions are: vehicle type; engine technology; vehicle age; fuel type; loading mass; after-treatment system; cold start conditions; road type; regions; traffic conditions; weather.

Non-exhaust sources (e.g. brake, tyre, road surface) contribute significantly to road traffic-related PM emissions. Brake wear has been recognised as one of the most important sources of non-exhaust emissions. The difficulties associated with the study of brake wear particles include: physical-chemical characteristics of brake wear particles are different; generation mechanism and rate variation; and the wide variety of sampling methodologies and measurement techniques used.

The wear rate (or emission factor) of brake depends on road conditions, driving behaviour, traffic intensity, etc., which can partly explain the wide range of values observed. There are functional relations that predict the quantity of brake wear emitted per distance driven, under typical driving, in particular braking, conditions. On the other hand, a set of standardised measurement and sampling procedures are needed.

The main conclusions on tyre wear are:

- Available data indicate exhaust and non-exhaust sources contribute almost equally to total traffic-related emissions. Among non-exhaust sources, tyre and road wear particles can contribute from 5% to 30 % by mass to non-exhaust traffic-related emissions. Tyre wear particles represents between 1%-8.5 % by mass to PM_{10} emissions. Among tyre wear particles, only up to 10% are PM.
- Given the variety of factors that influence the generation of tyre wear particles, any future efforts at reducing this source would need to consider not only the characteristics of the tyre, but also the vehicle to which it is mounted, the manner in which the vehicle is operated and the type of road surface on which the vehicle is driven.
- As varied sampling and analysis methodologies have produced non-comparable and in some cases even contradictory results, a single methodology should be developed to produce reliable and comparable results.
- The most important chemical constituents of tyre wear are comprised of both coarse and fine particle fractions. Despite the fact that some research regarding organic constituents of wear particles has been conducted, there is very limited information regarding organic composition of tyre wear particles.
- The available information on tyre wear particles requires collation, and the methodologies currently employed to measure and model emissions should be summarised in order to provide general recommendations for model development.
- Tyre wear involves mechanical processes, thermos-mechanical and thermochemical processes. These processes result in different size distribution of tyre wear particles. Size distribution is extremely critical parameters, because the airborne particles generated from tyre wear seriously harm the environment and human health and are likely to become one of the restricted non-exhaust emissions.

2.1.3. Key “Driver” results from WP3: Impact of User Behaviours

The Emission Measurements task in WP3 measured the amounts of emissions generated, and simultaneously characterised the driving behaviour, in order to establish a connection and correlation between measurable driving parameters and amounts of emissions, to be used in developing the basis for low emissions driving.

An exhaust emission measurement campaign conducted with six passenger cars driven by a pool of fifteen drivers on a single route near Helsinki provided a good set of accurate measurement results to be used in developing the equations that describe the relationships between driving parameters and different emissions species. The driver pool consisting of drivers between 30 and 64 years of age and both genders, and their driving experience ranged from 12 to 44 years. They were drafted amongst the employees of VTT, and with some exceptions they all drove four petrol-fuelled and two diesel-fuelled cars, fitted with a PEMS unit (Portable Emission Measurement System) – See Figure 2.

Figure 2: PEMS system installation on one of the five test cars (this one is a Skoda Octavia 1.5 TSI)

The test route was about 30 km long in the Espoo area (west of Helsinki, Finland) and was composed of mainly urbans streets but also sections of rural-type road, motorway and dual carriageways (see Figure 3). Each test driver drove the route twice in succession.

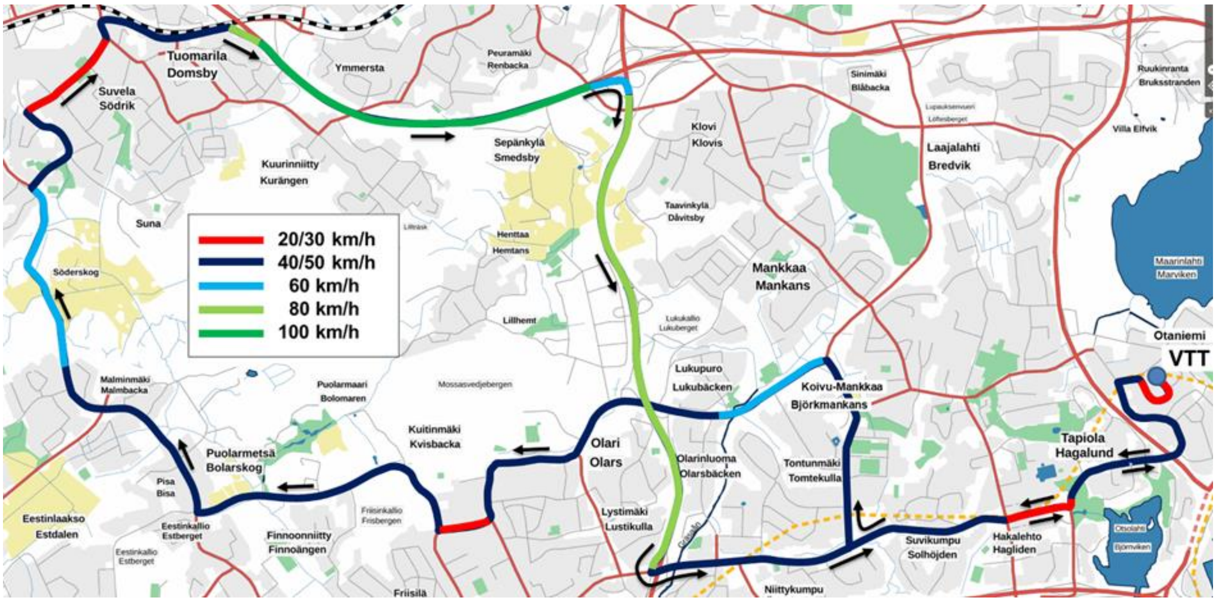

Figure 3: Test route schematics and speed limit sections

The high-level analysis based on the main descriptive parameters of driving (average speed, average engine speed, total work over trip) and the resulting fuel consumption, as well as measured levels of exhaust emissions revealed that amongst the drivers, there were distinctly some drivers that were able to constantly drive with low emissions output, while retaining also low fuel use. On the other hand, there were also some drivers that drove with high emissions and used a lot of fuel, and whose driving was also less consistent. This provided a good standpoint on developing the description of low emissions driving guidelines in WP5.

MODALES included a novel way of accurately measuring how the way of applying the brake affects the amounts of brake particulates dissipating from the brake. It was based on the latest version of the common inter-laboratory methodology to independently measure non-exhaust brake-related emissions in terms of particle matter (PM) and particle number (PN), developed in the PMP Particle Measurement Informal Working Group under the UNECE umbrella, and was implemented in the Brembo brake dynamometer test set-up, which was one of the test set-ups that have been used to develop such methodology.

To address the role of the drivers and their driving behaviours on brake emissions, some modifications were applied to this reference cycle, in order to reproduce a more conservative driving and braking progression. For this purpose, some of the braking events were modified according to the MODALES guidelines for low emission driving (Deliverable D5.1). In particular, the simulated vehicle decelerations and the initial braking speed of the most demanding stops have been reduced. All these modifications simulate a higher attention of driver to the traffic situations, and thus lead to a more conservative driving behaviour with less use of brakes. Furthermore, with the aim of replicating the same trip, the total length travelled by the vehicle over the test cycle, and the number of the braking events have all kept equal to the reference WLTP-Brake. From this experimental activity, it was clear that a significant reduction in the emissions coming from the wear of the braking components could be achieved with a more conservative driving behaviour.

Tyre wear emissions were addressed. As it is very challenging and difficult to measure, how the tyre emits particles due to the abrasion of the road surface, the relationship between driving behaviour and tyre wear, resulting in particulate emissions, were addressed with an on-road test campaign. For this purpose, a pool of drivers was recruited from Rome and Milan in Italy, and Athens in Greece, and a total of 76 drivers and their vehicles participated. With the aid of an OBD dongle and associated on-board data acquisition system, characteristic driving parameters were continuously measured and recoded during driving and collected in a cloud server. The most important parameters were longitudinal and lateral acceleration, as well as speed of the vehicle. Tyre wear was recorded with measuring the depth of tyre grooves with three-month intervals, and the loss of material was subsequently calculated.

A clear difference was found in tyre wear between front and rear tyres, mainly due to the fact that all participating cars were front-wheel driven, which tends to put much more load on the front tyres, because they are responsible for both traction (longitudinal loads) and steering (lateral loads), whereas the rear wheels are just “free rolling” with much less forces applied. Apart from this quite obvious result, the effect of vehicle make/model and tyre size was also addressed, as well as different types of tyres (compounds).

The analysis revealed that tyre wear measurements vary substantially between tyre positions, vehicle types, tyre sizes as well as tyre types, and the collected data contained a considerable number of outliers. As the fleet size was quite limited, it was not clear whether this variability was acceptable and genuine, and caused by the different local road and environment conditions or was resulting from errors in the measurements. This also suggested that if the important factors in the driving behaviours, which result in outlier measurements, are not known, predictive models for simulating the tyre wear may not perform well.

Nonetheless, an attempt was made to quantify the link between tyre wear and driving behaviour by modelling. The work started by taking only a few major driving behaviour parameters and using a simple linear regression model for tyre wear prediction, and taking the average values for longitudinal accelerations, lateral accelerations and vehicle speeds as independent variables. However, this led to a poor correlation, indicating that the average values of longitudinal and lateral accelerations as well as vehicle speed cannot explain the variability of tyre wear measurements. Therefore, a more complex, non-linear modelling was implemented, with a more sophisticated non-linear fitting method based on machine learning, including classification, regression, and ranking tasks. As the result of this exercise, an adequate level of understanding about the relative importance of featured parameters affecting tyre wear rates was achieved.

The effect of vehicle servicing on exhaust emissions was studied with two pools of cars consisting of six petrol-fuelled and five diesel-fuelled models. Two cars were originally type approved by EU4 regulations, and the rest represented various levels of EU5. All cars were tested using both a legislative cycle (NEDC) and a non-legislative, real-world type of cycle (ARTEMIS Urban). Cars were tested prior to the service, and shortly after service and maintenance was applied to them. The service included change of motor oil and filter, as well as change of intake air induction filter. For petrol-fuelled cars, spark plugs were also renewed to maximise the effect of service, even if the service schedule was not calling it.

The results of this work showed that applying service and maintenance did not univocally meant lower exhaust emissions and/or fuel consumption, as expected. Moreover, the results varied highly between cars, emission components and test cycles. However, petrol-fuelled cars responded overall more positively than those with diesel engines, even if the diesel-fuelled cars had on average much higher odometer readings. This led to a conclusion that modern engine management is able to maintain proper performance even if the regular maintenance schedule is not closely followed. However, this does not mean that service and maintenance are not important, because they may reveal such malfunctions that can lead to high emissions, even if we could not encounter such cases in this exercise.

Finally, a task was carried out to quantify the relationship between the user's driving behaviour and the resultant vehicle emissions from three sources (i.e. powertrain, brake, and tyre), respectively and in combination. A set of advanced mathematical and statistical models were developed to produce accurate estimates of vehicle emissions from all the three sources as a function of driving behaviour indicators which will be monitored and calculated during the user trails in eight European cities as well as the City of Nanjing (China), later in the project. Any behavioural change – as a result of training and education for low-emission driving – will be analysed and used to assess if it leads to a reduction in vehicle emissions.

The specifications of these models were derived from the state-of-the-art knowledge of low-emission factors gathered together in WP2, as described above. The model specifications were then finalised in line with performance criteria and indicators set up in WP6 for user trials and evaluation. These models were calibrated and validated in two steps. Firstly, the results generated by these models were compared to published scientific studies to ensure that the most advanced modelling theory is taken into consideration and adopted (or improved whereas appropriate) to meet the project's objectives. Secondly, the emission measurements and corresponding driving behaviours, provide limited but valuable reference data for the models to be further calibrated and validated. This increases confidence in the models' outputs.

Based on the preliminary data analysis, the collected emission measurements were further analysed to determine if the real-world or in-lab data can be used to derive mathematical models. It was concluded that:

- The PEMS exhaust data is accurate and adequate (second by second) for instantaneous emission modelling, with a high level of agreement with the prediction of the models.

- Brake wear measurements collected in-lab are also accurate and reliable and can be used to directly validate the results of the mathematical models as both have the same output frequency.
- Real-world wear measurements of the left tyres were collected every three months or so. As the actual corresponding driving behaviour data (e.g. acceleration, speed) cannot be made available for analysis due to data privacy and business interest, the behaviour data are classified into bins/categories. Analysis shows that tyre wear measurements exhibit a high degree of asymmetry with outliers far away from the average value. Simple linear regression models fail to correlate average categorical accelerations (both longitudinal and lateral) and vehicle speed to tyre wear. More advanced non-linear models (e.g. the XGBoost non-linear fitting method), seem to be able to improve the correlation considerably, with a R square value of 0.846 (compared to 0.102 for the best simply linear regression model), due to their capability of capturing the skewness and peaked-ness of the tyre wear measurements.

To overcome the limitations on vehicle types, driver behaviours and many other factors such as road and traffic conditions in the measurement campaigns, a set of simulation tools and models were developed:

- A GT-suite vehicle model to simulate exhaust emissions. This consists of engine performance map, gear number, gear ratio, and other vehicle parameters such as body dimensions and shape. It is also able to take into account the effect road parameters, environment conditions on vehicle emissions and energy consumption. The results show that the vehicle model produces highly accurate emission estimations, and able to be used to simulate various driving behaviours and speed profiles. This enables the development of the mathematical model for exhaust emissions to be implemented in the MODALES user trails.
- A Finite Element Analysis model was developed to simulate the brake wear resulting from the contact behaviour on a microscope size scale. Calibrated and validated by the dyno bench tests carried out by project partner Brembo, this is able to produce brake wear for various brakes and under various driving conditions. The simulated results are then used to quantify the importance of Key Performance Indicators (KPIs) related to driving behaviour.
- Similarly, a model was also developed for the simulation of the wear on the left tyres. The model is built in ABAQUS which provides a rich library of tyre and road surface parameters. It is particularly useful given that real-world tyre wear is measured over a long interval (e.g. > 3 months) and the corresponding driving behaviour data is not available.

The modelling work completed by drawing a conclusion on the importance of behaviour-related KPIs, as summarised as follows:

The top five important KPIs for powertrain emissions are:

1. The proportions of acceleration > 0.9 m/s2 duration in the total travel time

2. Average acceleration in the journey

3. The proportions of speed interval of 20~50 km/h in the total travel time

4. Average driving speed in the journey

5. Average driving speed in the journey without the stop events.

The top five important KPIs for brake wear emissions are:

1. Deceleration rate of braking

2. Average deceleration rate when braking

3. Braking distance

4. Braking time

5. Initial speed when braking.

The top five important KPIs for tyre wear emissions are:

1. Deceleration rate when braking on bends (curves)

2. Acceleration rate when accelerating on bends

3. Initial speed when braking on bends

4. Initial speed when accelerating on bends

5. Deceleration rate when braking on straight roads.

2.1.4. Key "Driver" results from WP5: Guidelines and Tools for Low-emission Driving

The task "Guidelines for Low Emission training" ensured the link between the theoretical aspects of the project and their validation and use during the experimentation phase (WP6) and awareness campaigns (WP7). This therefore considered the results of WPs 2 and 3 especially, in order to define guidelines for low-emission driving, and also to define tools to monitor and improve driving behaviour resulting in emission reductions.

In this context, a mobile (Smartphone) app is developed, complemented by a web dashboard addressed to public and local authorities, which can potentially provide them with a statistical overview of the data collected from users.

The main factor influencing emissions of all types is frequency of acceleration and deceleration. The aggressiveness of the driving style is much related to users, and recommendations to change that style are important for reducing emissions. However, this frequency may be influenced also by factors totally unrelated to driving style. Some of them are environmental or contextual factors, such as type of road and curvature, levels of congestion or wind influence. There is very little the user can do to change them. Similarly, other factors are depending on the vehicle, such as the type of engine or the weight. The user cannot change them.

Thus, a scoring methodology was needed to define what kind of recommendation the user should receive. The following stages are considered for scoring:

1. Calculation of RPA and v.a-[95] percentile both for positive and negative accelerations
2. Event identification and scoring through AI methodology like Random Forest methodology or genetic programming.

The main guidelines can be summarised as follows:

- When the engine is cold, accelerations and high speed should be avoided.
- Heavy accelerations should be avoided: at high speeds, high acceleration values cause an asymptotic increase in emissions except NO_X.
- Especially in urban environment, frequent accelerations should be avoided.

- High speeds should be avoided.
- When travelling downhill, engine braking should be used to prevent acceleration and high speeds.
- Lower engine torque and lower load will cause lower emissions. In windy weather speed should be reduced to eliminate further emissions due to additional torque requirement. A gradual increase of torque before entering the slopes will help emissions preventing sudden torque requirement.
- Use of air conditioning should be avoided as much as possible, if used sudden accelerations are to be avoided.
- Avoid braking with the clutch pedal pressed in order to take as much as possible advantage of the engine-brake torque.
- Pay attention to traffic situations ahead, a higher attention and anticipation by the driver will reflect a higher use of the engine to slow down the vehicle, reducing the need for braking and reducing exhaust emissions.
- Avoid rapid acceleration that can often be followed by strong decelerations. A conservative driving style without abrupt transition in the vehicle speed will lead to lower emissions.
- Use correct season tyres (Summer - Winter - A/S).
- Select route with low slope and/or higher straight line.
- Select route with lower traffic (at comparable distance).
- In case of available road characteristic info select road with low micro-roughness .
- Monitor / Keep correct tyre pressure.
- Control Tyre Wear Profile (Visual inspection) and assure proper Static Setting.
- Avoid overload or un-necessary weight transportation.
- Select Eco-driving mode option (where available).
- For Electrical Vehicles optimise Equilibrium between Battery Regeneration and Tyre Wear.
- Avoid high acceleration/deceleration both Transversal and Longitudinal.
- Reduce car (use alternative mobility solutions) usage in case of short Time (Thermal state of Tyre).
- Tyre position rotation.
- Keeping the tyres inflated to the recommended level. When tyres are not inflated properly, they increase the wear-and-tear of the tyre and fuel costs.
- Getting regular tune-ups will go a long way to increasing fuel efficiency and improving the lifespan of the vehicle.
- Changing the oil regularly will contribute to a cleaner engine and lower vehicle emissions.
- Keeping the air filter clean will also protect the environment.
- As exhaust emissions in modern cars are highly dependent on correct functioning of the exhaust after-treatment system (EATS), keeping its performance on a high level is of utmost importance. This is achieved with promptly reacting to the error messages of the OBD-system, and using only correct and certified spare parts. One should never tamper with the EATS.

The task “Functional specifications of tools” defined the specifications to develop the MODALES Smartphone app and web dashboard. The aim of these tools is to collect and analyse the driving patterns of individuals to adjust a user’s driving style, with a specific aim on emission reduction. To achieve that, relevant user information such as accelerometer, gyroscope, location and OBD data is be collected transparently and continuously. Based on the collected information, the system aims to provide two types of recommendations. On one hand, active recommendations will offer straightforward recommendations while the driver is on the way, which would reduce high-emission driving styles by providing immediate corrective actions. On the other hand, passive recommendations will be about analysing and understanding a user's driving behaviour patterns and contextual information (e.g., on traffic jams, weather) to generate a post-driving report that could be used for encouraging users for safe driving practices and possibly offer rewards for good driving behaviour.

Deliverable D5.3 is the software solution itself. This is supported by a document on how the software solutions of the project have been developed. It complements the functional specifications and serves as a reference for understanding the functioning of the different modules developed and their deployment and maintenance in the future.

For each app user, anonymous indicators are transmitted to a web dashboard to collect usage statistics and performance metrics. The latter allows the authorities and potentially the public to understand the benefits of the mobile app and view statistics by region or type of user. The web dashboard aggregates the data and presents them in various graphical representations to assist decision-making.

Figure 4: Dashboard web application

The web dashboard application is based on the received data from the mobile sensors and OBD dongles and indicators derived from them. The indicators include vehicle emissions, fuel consumption and driver's low emission performance. The three indicators are time-based. Thus, the dashboard can also present the performance evaluation based on time.

The dashboard is linked to an internal reporting platform, used for the data management in the trials in WP6. The data collected via the mobile app are, after post-processing on the LIST servers, stored in a PostgreSQL relational database. In addition to displaying statistical information, as illustrated in the screenshots below, it allows the automatic availability (every night) of the data sets for each trial site.

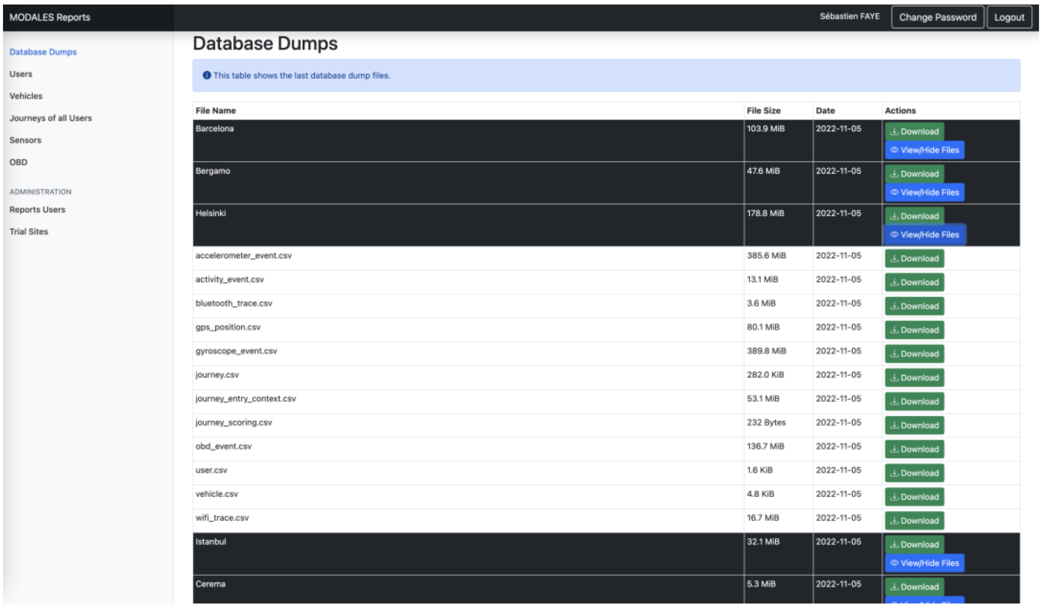

Figure 5: Reporting platform: dataset download for each trial site

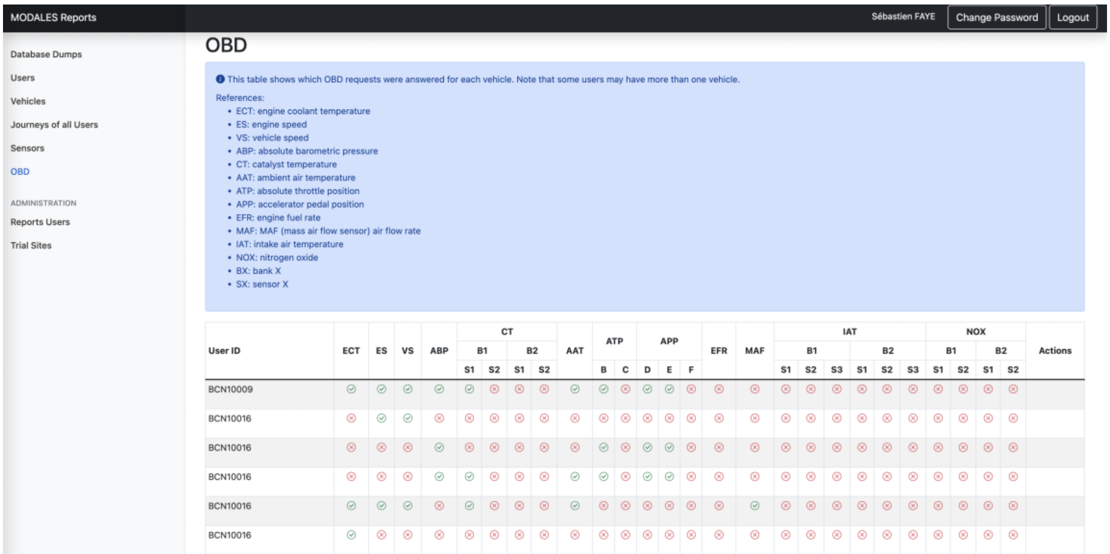

Figure 6: Reporting platform: OBD data collection analysis

For the app itself, which was developed for Android and iOS platforms, the following figure shows the overall architecture. Two main parts are described: the client side (the mobile app itself) and the server side (a mix of several components to collect, process, extend and store the data received from the app). Optionally, there is an OBD dongle that is connected to the vehicle using the OBD port and connected to the mobile device via Bluetooth.

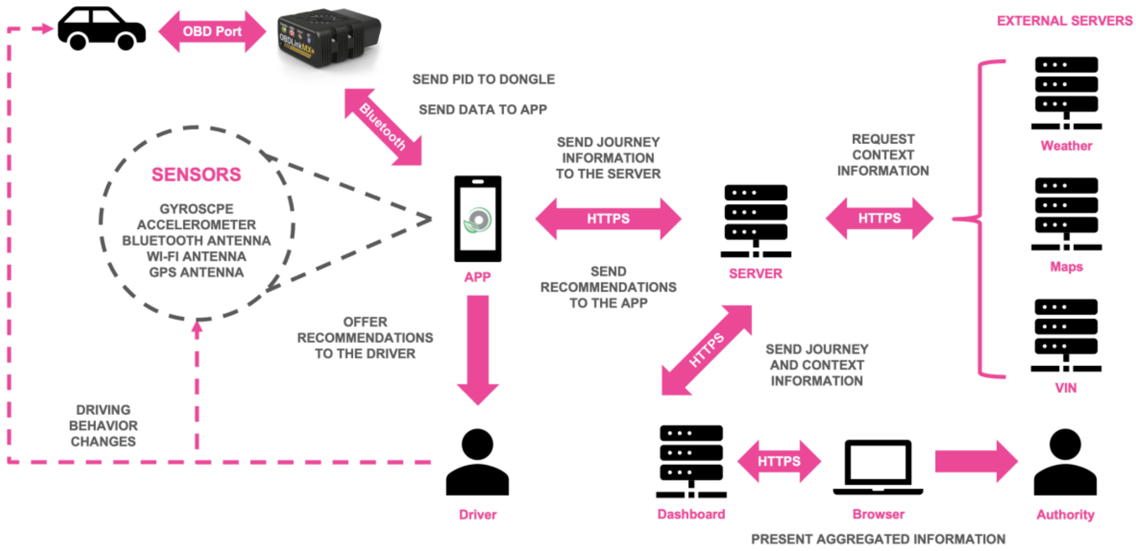

Figure 7: High-level architecture of the MODALES app

The OBD dongles were selected following a study carried out in WP4. The development operations were done in laboratory in a first step using an OBD emulator, reproducing messages in a realistic way in order to predict the behaviour of the mobile application and program OBD requests.

The main purpose of active recommendation is to make users react when poor driving behaviour is detected. Several approaches were considered, including gamification, complex interfaces, audio or text announcements, etc. In the end, the project adopted a simple, non-distracting approach for the driver, based on a colour code (see figure below).

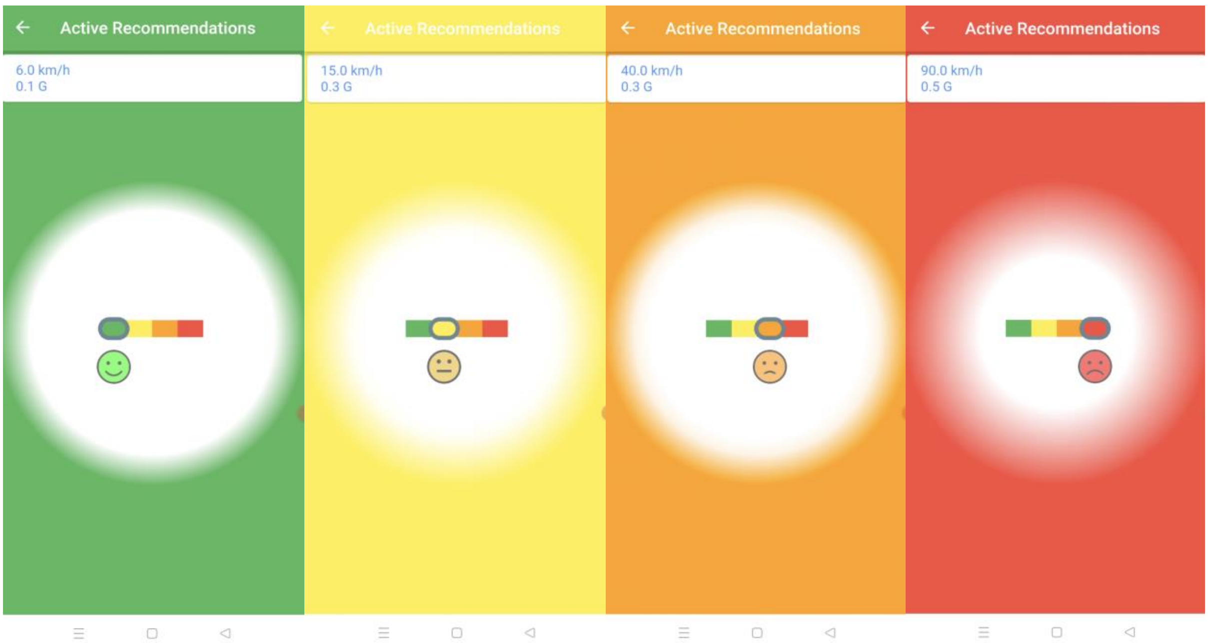

Figure 8: Active recommendation system of the MODALES Smartphone app

To do this, a score is calculated on the phone, in real time and with a very dynamic refresh rate so that the user can immediately see the effects of his/her driving on the system. It was decided that this score should allow the detection of situations where the driver would or would not have smooth or more aggressive driving behaviour.

It was initially thought that this score considers several metrics, such as the revolutions per minute (RPM), collected via OBD, or GPS speed, to calculate an acceleration/deceleration coefficient. The problem in both cases is that the collection frequency is usually more than one second, which prevents the application and the interface from being as responsive as possible. Furthermore, we did not want to create dependencies on external services or devices and avoid energy-greedy solutions. This score should be calculated locally on the phone and without external influence, even when offline.

The solution that was adopted was to consider the accelerometer incorporated in all smartphones on the market, and measuring the force experienced by the device on three axes (x, y, z). This sensor is permanently used by smartphones to detect the user's activity and consumes very little energy. Moreover, the sampling frequency is usually 100-200 milliseconds which is perfect for this application.

A post trip scoring system was also incorporated to give the driver realistic feedback about his/her driving profile as to optimise the total emissions. The score calculated must be related to the total emissions including the particles emitted from the brakes and tyres. The scoring methodology as selected uses an AI system with random forest algorithm.

The first step is the determination of the events and the related features. Then calculations for RPA (relative positive acceleration) are carried out and the features for emissions are deduced. These features are input to random forest algorithm for training. Training leads to the score determining the threshold values for each velocity acceleration combination and the multiplier factors in relation to RPA values. The following diagram depicts the main flow chart for the algorithm.

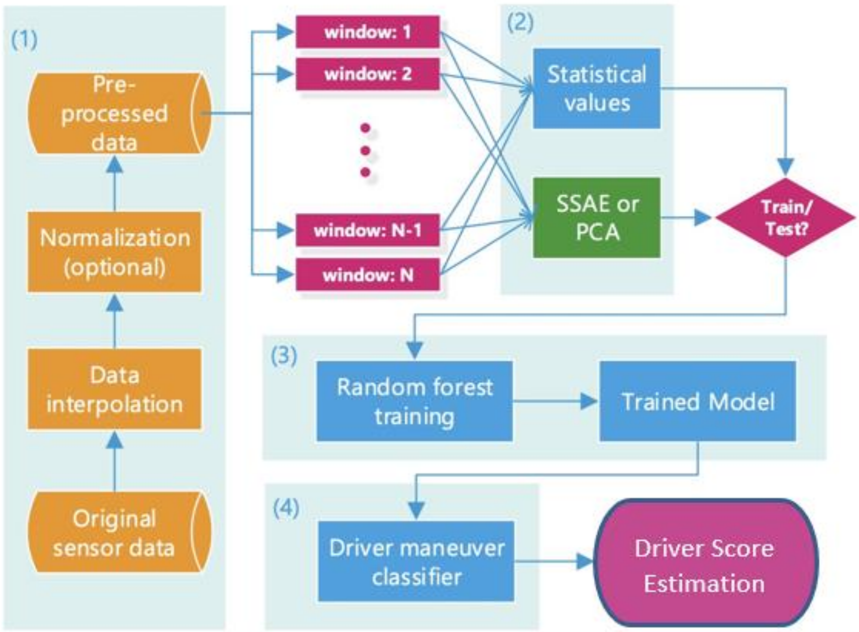

Figure 9: Scoring methodology for passive recommendations

This system is flexible, and it can be trained for any vehicle type with the condition that there is training data existing for that type of vehicle with precise emission values.

Testing and technical verification of the mobile app and the dashboard web application were carried out. This mobile app was then tested with volunteer drivers in several locations across Europe (trial sites) as part of WP6 (below). Testing was performed on the data storage, performance evaluation of the procedures, queries and the overall functionality related to the data storage, as well as analysis of source code quality and verification, including static code analysis, maintenance of code quality, bugs detected inside the source and detected security vulnerabilities.

Initial user acceptance of the app was collected using the System Usability Scale (SUS) for evaluating the usability of the app. 41 participants responded (representing all seven trial sites). The responses on a scale of 1-5 converted to a score of 62 which is considered "good", considering that the app is a research prototype and was still under fine tuning until the end of the trail period in 2023. As well as the 10 questions included in the SUS scale, all trial-site participants were asked to notify any technical issues they encountered while using the app. All issues were listed, and solutions were given by the MODALES development team.

In conjunction with the app, a MODALES Training courses manual for low-emission driving was produced (confidential deliverable D5.5), which planned the MODALES training activities regards to the driving behaviour and the use of the MODALES Smartphone application. The trainings aimed to improve the driving behaviour of different types of drivers such as drivers of private cars, truck drivers and van or taxi drivers, focusing on the drivers' age, country and external environment and driving profile. Due to ongoing COVID-19 restrictions at this time (2021), the project decided to produce training videos rather than carry out face-to-face training sessions.

Videos were produced for car drivers in eight language versions (either with dubbed voiceovers or subtitles), covering the countries of the WP6 trial sites. There were spoken versions in English, French, Italian and Spanish, and subtitled versions in Finnish, Greek, Turkish and Chinese. In addition, English versions of videos for taxi/LDV and HDV drivers were produced (with subtitled versions in Chinese).

Figure 10: Filming of the MODALES HDV training video in Belgium, with the kind cooperation of DB Schenker

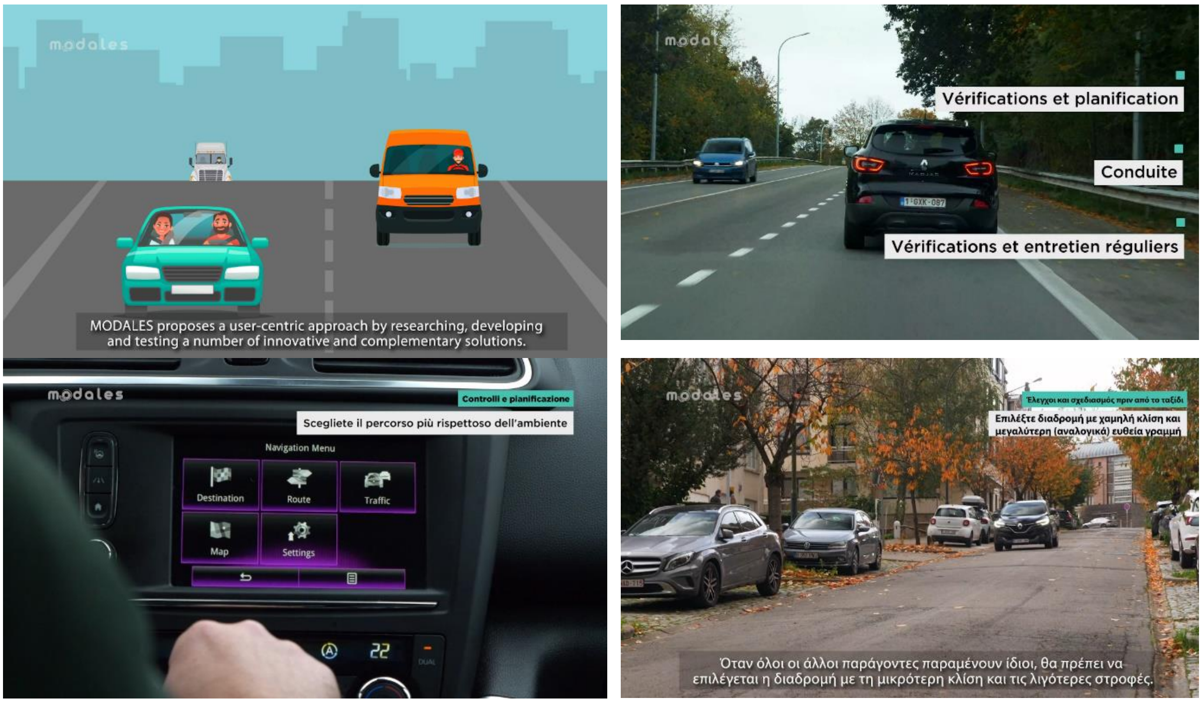

Figure 11: Selection of screenshots from the MODALES car training video, showing versions in English, French, Italian and Greek

The videos, around 15 minutes in length, were used for the trials in WP6, then after the trials they have been made public online on the following media:

- ERTICO YouTube channel: https://www.youtube.com/@ertico-itseurope4691/videos
- Links to the above from the media section of the MODALES website (https://modales-project.eu/media
- The Chinese versions are also available on the video sharing site Bilibili (>335m monthly users): https://www.bilibili.com/video/BV1bg411W7nj/?vd_source=f44a9ea5948d0950fb14cfd32c1616a1

2.1.5. Key "Driver" results from WP6: User Trials and Evaluation

An evaluation methodology (D6.1, confidential) was produced, in which high-level Research Questions were set, which should be answered by the evaluation process. Each RQ is associated with a hypothesis and will be measured by one or more performance indicators. This covered not only the "Driver" part of the project but also the other three areas below.

This was followed by a ramp-up process for the real-world trials of the MODALES driving assistance tools (training and app): their functionality and effects on driver acceptance and performance. This trial ramp-up phase took place in Barcelona and Luxembourg, covering aspects including the choice of vehicles, selection and briefing of participants, management of trial participants (procedures, mitigation measures to deal with participants who drop out or do not participate as expected), choice of driving routes and timing of the trials.

The full trial sample group consisted of 170 individuals, including both private and professional drivers. During the initial phase, referred to as the baseline period or Phase 1, drivers did not utilise any MODALES tools. The duration of this period varied between 1 and 3 months due to the delayed availability of the app. Some drivers who started earlier had an extended baseline period while awaiting the full version of the app, which included driving advice. The trials took place in seven cities/regions in Europe (in Finland, Greece, Italy, Luxembourg, Spain, Turkey and the UK), as shown in the figure below.

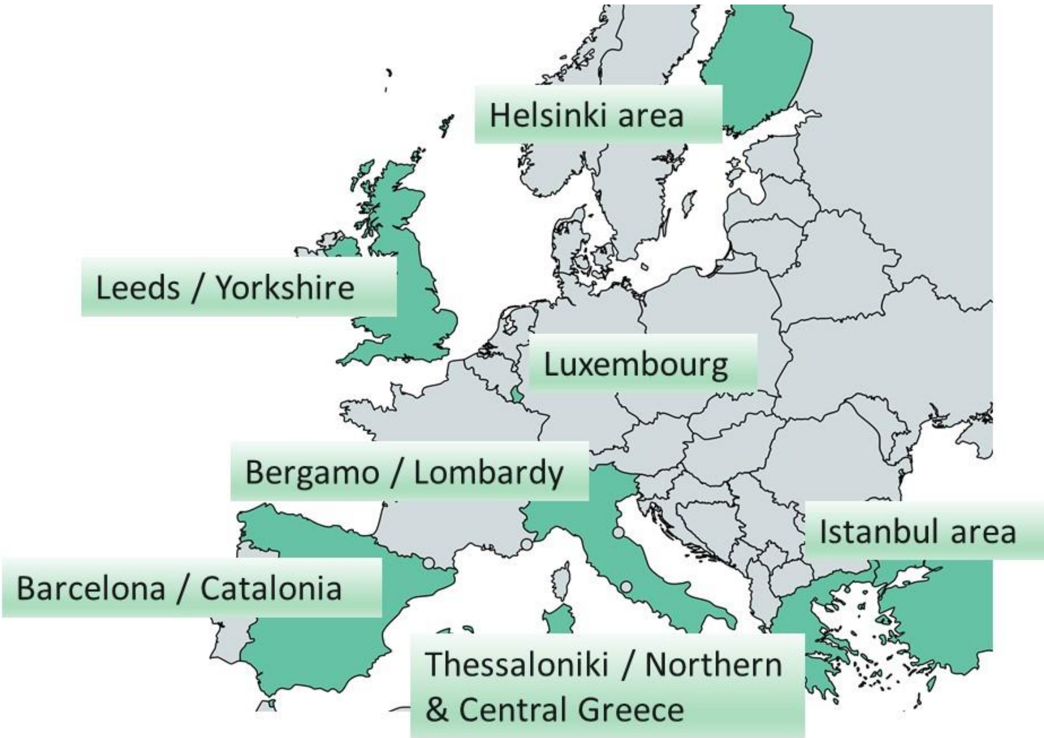

Figure 12: The MODALES training and app trial sites in Europe

At the end of Phase 1, the participant was asked to view the training video (developed in WP5, described above). This included a general introduction and common methodologies for all types of vehicles with subsections for pre-trip, trip and maintenance aspects aiming at low emission driving.

Phase 2 lasted approximately 2 months on average, but for certain users who joined later, it had to be condensed into a shorter period. In this phase, drivers were required to use the MODALES tools, which involved using the app on smartphones with an installed OBD reader whenever possible. The data collected during this phase was stored on the device and regularly transmitted by the user or the mobile device itself to the central server at MODALES partner LIST, located in Luxembourg.

To gain a deeper understanding of the impact of the MODALES driving assistance tools and to quantify the extent of emissions reductions in real-world driving scenarios, two additional field tests were carried out, which were not originally included in the project plan. The first field test was conducted in Finland by partner VTT, specifically focusing on Portable Emissions Measurement Systems (PEMS) measurements with and without the utilisation of the MODALES app. The second test was conducted in Greece by partner CERTH, with the objective of measuring the concentration of particulate matter (PM) ranging from 0.3 to 10.0 µm in diameter.

Three surveys were conducted among the MODALES trial participants. The first was the driver selection survey, which was administered individually by each participating project partner. The second survey followed the viewing of the training video by each participant and focused on their understanding and acceptance of the video, the extent to which they learnt good practices and any other feedback. 85 % of the respondents found the content of the video very clear. 61 % answered that the information provided by the video was very useful and very complete. Overall, the feedback on the training videos was very positive and they are a useful resource that can and will be disseminated more widely.

The final survey, after the end of Phase 2 of the trials, was on the use of the MODALES app and the extent to which drivers felt their driving style and behaviour had changed. A total of 69 users from various European trial sites completed the final questionnaire. However, participants in China were excluded from the distribution of the questionnaire due to legal restrictions preventing them from using the app. Around a third of the respondents used the app every time they drove during the trial period. Users generally considered that the MODALES app successfully encouraged behavioural changes in driving, with many respondents reporting a reduction in poor driving behaviour. However, some issues were raised with the app's design and functionality, and that a better performing and more stable version of the app (a commercial application rather than a research project) would be welcomed by most respondents.

The **results of the trials** showed differential influences of driving behaviour on the three types of vehicle emissions were studied individually and in combination.

For the differential influences of driving behaviour on **exhaust** emissions:

- Low-emission driving training programmes (training video and MODALES app) have shown the potential to contribute to reductions in mean values of NOx emissions in most of the seven European cities evaluated.
- Individual drivers displayed variations in their impact on NO_X emissions. Nevertheless, the training programmes proved to be effective in reducing NO_X emissions for the majority of participants across all road types.
- The low-emission driving training programmes successfully decreased NO_X emissions for both female and male drivers. However, female drivers experienced more significant reductions compared to their male counterparts.
- Most novice and experienced drivers experienced a reduction in NO_X emissions after participating in the training.

Site	Best	Worst
Leeds	-6.1%	+2.3%
Helsinki	-10.9%	+2.9%
Barcelona	-4.9%	0.0%
Luxembourg	-4.5%	+2.9%
Istanbul	-1.8%	+7.0%
Thessaloniki	-1.8%	+6.0%

Figure 13: MODALES trials: Exhaust emissions (NO_X reduction before and after training and app) – Best vs worst performance (Median reduction -3.1%)

The differential influences of driving behaviour on **brake wear** emissions:

- There were significant reductions in brake wear emissions in most cities, while Istanbul had slight reductions. Barcelona demonstrated the most substantial improvements. Overall, the implementation of low-emission driving training contributes to a more sustainable and healthier environment.
- Motorways exhibited the highest mean values of brake wear $PM_{2.5}$ and PM_{10} emissions per stop, followed by rural and urban roads. This is likely due to the higher average speeds on motorways, leading to more intense braking and increased brake wear emissions per stop.
- Individual drivers exhibited variations in their impact on brake wear emissions. Overall, the training proved effective for most users in reducing brake wear emissions on all road types.
- The low-emission driving training and app contributed to reducing brake wear $PM_{2.5}$ and PM_{10} emissions for both female and male drivers. However, male drivers experienced greater reductions compared to female drivers. Further research is required to understand the underlying factors and develop targeted interventions to achieve comparable emission reductions for female drivers.
- Experienced drivers had lower initial brake wear emissions compared to novice drivers. After participating in low-emission driving training, both groups showed improvements, but novice drivers experienced a greater reduction in brake wear emissions.
- The results revealed a difference ranging from 4-10 % in the total concentration of 0.3-10.0 µm size particles emitted from the brakes when using the App. The reduction in brake particle emissions is strongly related to the smoother driving style that the driver has adopted following the MODALES recommendations (42 % - 140 % reduced median deceleration with the App activated).

Site	Best	Worst
Leeds	-41.3%	-7.1%
Helsinki	-64.4%	-10.0%
Barcelona	-31.4%	-7.6%
Luxembourg	-36.0%	-3.3%
Istanbul	-37.8%	-1.3%
Thessaloniki	-33.8%	+4.8%

Figure 14: MODALES trials: Brake wear ($PM_{2.5}$, PM_{10}, mg per stop, before and after training and app) – Best vs worst performance (Average -19.7%)

The differential influences of driving behaviour on **tyre wear** emissions:

- Low-emission driving training programmes can contribute to reductions in tyre wear emissions. Bergamo demonstrated the most substantial improvements in tyre wear emissions, while there was the least improvement in Thessaloniki.
- The mean values of tyre wear emissions were highest on motorway roads, followed by rural and urban roads.
- There were variations among individual drivers in terms of their influence on tyre wear emissions. However, the training demonstrated overall effectiveness in reducing tyre wear emissions for the majority of users across all road types.
- The training and app successfully decreased tyre wear emissions for both female and male drivers. However, male drivers experienced more significant reductions compared to their female counterparts.
- Following the training, novice drivers experienced a more substantial reduction in tyre wear emissions compared to experienced drivers.

Site	Best	Worst
Leeds	-6.0%	+2.3%
Helsinki	-14.9%	+4.4%
Barcelona	-7.1%	+1.7%
Luxembourg	-5.5%	+1.2%
Istanbul	-11.3%	-4.5%
Thessaloniki	-4.2%	+0.2%

Figure 15: MODALES trials: Tyre wear (mg mass loss per km, before and after training and app) – Best vs worst performance (Average -3.28%)

The differential influences of **journey-based driving behaviour** on **combined emissions**:

- Overall, total scores have improved in phase 2 as a result of the training intervention, while the level of improvement varies from site to site.
- The greatest percentage change was shown by the Bergamo site (16%), followed by Barcelona (12%). Paired t-test and Wilcoxon test showed significant difference between phase 1 vs. phase 2 at all sites. In contrast, the levels of PM emission, total emissions and fuel consumption decreased in phase 2. This demonstrates that the training and active recommendations by the MODALES App have helped drivers to improve their driving behaviour and as a result pollutant emissions have decreased in phase 2.
- Total scores have increased in phase 2 for urban and urban-rural trips, whereas the score has decreased on urban-motorway and urban-motorway-rural trips in Leeds where such data was available.
- Total score decreased in phase 2 for the age groups 30 – 49 and 65+, whereas total score increased in phase 2 for 20 – 29 and 50 – 64 for Leeds. The 30 – 49 age group also demonstrated

a reduction in total score in phase 2, whereas the score increased for the other two groups for Helsinki.

- Regarding gender difference, the low-emission driving training and app successfully decreased NOx emissions for both female and male drivers. However, female drivers experienced more significant reductions compared to their male counterparts.
- Also, most novice and experienced drivers experienced a reduction in NOx emissions after participating in the low-emission driving training.

For full results, including those from the separate PEMS tests, the Nanjing case study in China and a separate case study on hybrid and electric vehicles (not part of terms of reference of MODALES), see Deliverable D6.3.

An impact assessment based on the COPERT software was conducted for the MODALES app and training, based on the trial results. This software is used to compare baseline vehicle emissions for some European countries (Finland, Italy, Spain, Turkey, Germany, and France) with the estimated emissions after the implementation of MODALES solutions. It specifically measures the emission savings by estimating air pollutant emissions and greenhouse gas emissions from road vehicles for the following pollutants: CO2, CO, NOx, and PM. The impact is based on trial data from Finland, Italy and Spain only, as these countries had the most trial participants and also reliable vehicle stock data. Potential impact on two other large EU Member States where trials did not take place (Germany and France) was also carried out, as vehicle datasets were available. The potential impacts are further described in Section 3 of this report.

2.1.6. Key "Driver" results from WP7: Awareness, Communication and Dissemination

WP7 of MODALES included a driver awareness campaign, which made extensive use of the project outputs and communication tools to give visibility to MODALES and to promote the low-emission driving guidelines and training to private and professional drivers in targeted countries. This included promotion to bodies such as motoring organisations (e.g. member clubs of FIA), driving schools, road transport operators and their associations/forums (e.g. IRU) and to public authorities. This online campaign targeted different media at users appropriate to their country (language) and sector (motorists, HDV drivers).

The campaign commenced at the beginning of 2022 with a duration of just over a year. It provided short and impactful messages in graphical form to advise on different aspects of low-emission driving behaviour and associated actions (such as maintenance and trip preparation). The messages were developed based on the guidelines and training videos from WP5. They were disseminated in the form of:

- A set of ten simple infographics, containing one message/guideline, for inclusion on social media sites of partners or other stakeholders (using the hashtags #MODALESproject and #MODALEStips specific for the campaign). These are available in 11 different languages;
- Short and user-friendly guidance documents (one or two pages, also available in different languages) available on the MODALES website which are linked to from the above social media campaigns in order to provide a greater depth of information and guidance;
- Making the training videos publicly available online on the MODALES website and on YouTube (see under WP5 above).

The driving tips were especially aimed at petrol and diesel car drivers and they divided into three categories: 1 - before driving, 2 - while driving, and 3 – car maintenance. Each tip was accompanied by an explanation, and all information is accessible on the MODALES website at https://modales-project.eu/campaign

Figure 16: Examples of the tips in the three different categories

The awareness campaign with MODALES tips was launched in March 2022 and was implemented until the end of February 2023.

The campaigns included at least two social media posts per month in the countries covered. FIA Region I led the MODALES awareness campaign to share low-emission driving tips and to encourage professional and private car users to adopt good driving behaviours and maintenance practices. To achieve this objective, FIA worked with Member Clubs, such as ACA (France), ACI (Italy), ADAC (Germany), ACL (Luxembourg), ÖAMTC (Austria), RACC (Spain), and TCS (Switzerland), seeking support through their network, to reach the Clubs' members in different countries. By working closely together with Member Clubs, FIA Region I aimed for the MODALES awareness campaign to reach as many drivers as possible.

2.2. Innovation Area "Retrofits"

2.2.1. MODALES Innovation Solutions in the Retrofits Innovation Area

- Diesel-saving technologies for cars and vans
- NOxBUSTER for buses and trucks
- Diesel particulate filter servicing

2.2.2. Key "Retrofits" results from WP2: Defining Low-emission Factors

The literature review in WP2 (see Deliverable D2.2) included the potential impact of retrofitted Engine Aftertreatment Systems (EATS). This was more 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 NO_X 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 (Non-Road Mobile Machinery – NRMM), the usage and installation varies considerably. This sets a higher cost for design and testing for approval. Retrofitting the 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.

2.2.3. Key "Retrofits" results from WP4: Effectiveness of Inspections and Depollution Systems

Retrofits related work in WP4 studied the feasibility and potential of retrofit emission controls, and experimented with prototype technologies for after-treatment that will retrofit passenger cars and HDVs targeting at dramatic reduction of NO_X from diesel engines.

The task started with a thorough State-of-the-Art review of potential retrofit innovations, and a comprehensive analysis of seven widely recognised retrofit technologies, namely Selective Catalytic Reduction (SCR), Lean NO_X Trap (LNT), Ammonia Creation & Conversion Technology (ACCT), Ammonia Storage & Delivery system (ASDS), Thermal Insulation Technology, Electric Heated Catalyst (EHC), and External Burner. The analysis showed that each of these technologies has its own pros and cons, in terms of Response Time, Energy Penalty, Complexity, and Effectiveness. Overall, ACCT offered a good balance between these performance indicators, and was thus selected for simulation and modelling carried out later in the task, together with SCR as a benchmark which is the only retrofit device commercially available.

Both in-lab and real-world experiments of the retrofit SCR system for light commercial vehicles were carried out on Mercedes-Benz Sprinter Euro 5 models with 4-cylinder 2.2 litre diesel engine. All those vehicles have a Diesel Particulate Filter (DPF) as original after-treatment system and that was left in place without any modifications.

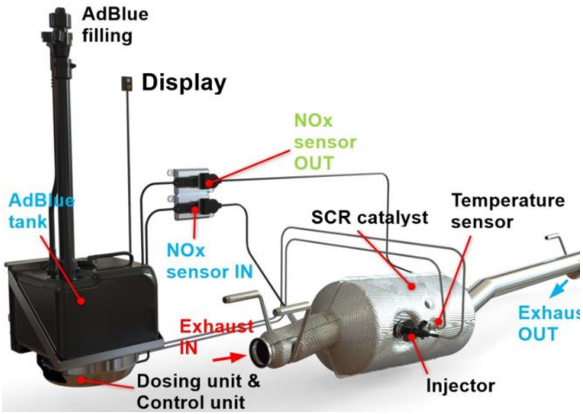

Figure 17: Operation principle of retrofit SCR system

Figure 18: Test: NOxBUSTER City Light retrofit SCR system installed to vehicle

During early phase testing it was noted that this type of vehicle has very low exhaust gas temperatures at city driving speeds and on the other hand very high exhaust gas temperatures during DPF regeneration. Low temperature SCR may not handle temperatures above 500°C and therefore SCR material was changed to withstand up to 600°C during active DPF regeneration. Another challenge was possible hot shut down of engine during DPF regeneration, leading to overheating of urea nozzle. The tests proved that Euro 5 vehicles are optimised for the New European Driving Cycle (NEDC) and does not correlate well with the Worldwide harmonised Light vehicles Test Cycles (WLTC) results in general. A NO_X reduction of more than 50% over the whole cycle may be achieved depending on test cycle and operating conditions. The reduction (or NO_X conversion efficiency) was much greater when the retrofit system active (sufficient exhaust gas temperatures (EGT) reached), highlighting that retrofit SCR efficiency is highly dependent on the engine out exhaust temperature. Outdoor tests confirmed that the effect of ambient temperature for engine raw NO_X (and CO_2) is significant and ambient temperature affects tail pipe NO_X especially when EGT is lower than the SCR-activation threshold.

Figure 19: Emissions and fuel consumption test facility with a single-roller 2WD dynamometer

Finally, the task carried out sophisticated simulation and modelling of the ACCT and SCR retrofit innovations for passenger cars.

2.3. Innovation Area “On-Board Diagnostics”

2.3.1. MODALES Innovation Solutions in the OBD Innovation Area

- More robust and durable emission control systems
- Enhanced OBD functionality as an anti-tampering measure

2.3.2. Key “OBD” results from WP2: Defining Low-emission Factors

The literature review in WP2 (D2.2) covered On-Board Diagnostics (OBD) protocols, which differ in terms of hardware formats and software protocols. Since its early introduction in the 1980s by the California Air Re-sources 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 from the utilisation of the parameters to assess vehicle’s emissions vs. driving characteristics, MODALES investigated 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.

2.3.3. Key " OBD" results from WP4: Effectiveness of Inspections and Depollution Systems

WP4 (Deliverable D4.1) considered 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.

MODALES investigated 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, potential recommendations for a broader use of OBD were proposed, not only from a legal point of view, but also regarding the lack of available services or the avoidance of vehicle tampering.

2.4. Innovation Area "Periodic Inspections"

2.4.1. MODALES Innovation Solutions in the Periodic Inspections Innovation Area

- Enhanced inspection procedure to trap tampering
- Roadside emissions testing

2.4.2. Key "Periodic Inspections" results from WP2: Defining Low-emission Factors

WP2 carried out a literature review on the effectiveness of inspection and maintenance (I/M) programmes in Europe and the USA (see Deliverable D2.2). A vehicle 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.

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 Periodic Technical Inspections (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 (NO_X, PN). Also, amendments of PTI procedures are way behind the introduction rate of EATS in vehicles. Due to in-creasing 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 grams per gram 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.

A separate task in WP2 looked into the legal situation on tampering in different EU Member States. A comparative analysis was provided, identifying the commonalities and contrasts in legislation on vehicle tampering across EU Member States based on data collected through legal research questionnaires as well as a stakeholder survey. Some of the main findings regarding each topic analysed as part of this exercise are as follows:

- The EU legal framework regarding vehicle tampering: as part of the EU legal framework on type approval, defeat devices are generally and explicitly prohibited, and under EU law on vehicle inspections, both periodic roadworthiness tests and technical roadside inspections must check for (signs of) tampering, with a clear focus on odometer tampering.
- The relevant national legal and regulatory frameworks on vehicle tampering: the relevant Directives and Regulations are generally transposed and covered at national level by (often the same) national road and/or motor vehicle regulations.
- The obligations placed on manufacturers under national law: in the majority of Member States, aside from the rules applicable in the context of type approval processes, there seem to be no specific national legal requirements on manufacturers relating to the prevention of tampering, nor other specific requirements regarding tampering that manufacturers would have to meet.
- The national rules and requirements in place in relation to type approval: in most Member States, national legislation on type approval processes relates to Directive 2007/46/EC and mostly does not provide for provisions, which specifically target tampering. The national rules and requirements regarding post-type approval rules on tampering: vehicle tampering is prohibited under the national law in most Member States, but this prohibition most often is derived from legislation on type approval processes, rather than included as a specific legal provision.
- The national legislation in place regarding periodic roadworthiness tests and technical roadside inspections: several Member States provide for specific verifications in order to identify tampered vehicles or parts in the national legal measures relating to periodic roadworthiness tests, and some Member States seem to impose checks specifically related to tampering in the relevant national measures regarding technical roadside inspections.
- National strategies and initiatives regarding vehicle tampering: odometer data is often collected at Member State level and gathered in a national database, and there are many initiatives, often handled by public bodies, which help buyers of (mostly second-hand) vehicle to have access to the mileage history of a specific vehicle.
- The effectiveness of the rules on tampering and the enforcement of these rules: although studies conducted in the Member States generally identify their national rules and systems on tampering as proportionate and globally efficient, some gaps in national legislation at national level were identified, and that issues related to the effectiveness of the enforcement of rules on tampering and recalls identified at national level mostly relate to the lack of severity of the sanctions, although some practical obstacles were also found to exist.
- Relevant case law by national courts, bodies, or authorities relating to vehicle tampering identified in the Member States: most rulings did not rely on specific anti-tampering rules but rather on general consumer, contractual and/or criminal law (applying the concept of fraud or hidden defect).

2.4.3. Key "Periodic Inspections" results from WP4: Effectiveness of Inspections and Depollution Systems

Work in this area investigated the detection of tampering or malfunctions in vehicles by considering a wide range of technical, behavioural and legal criteria, in order to clarify the current and future capabilities of the EOBD protocol.

Drawing on the results, the current characteristics of the EOBD protocol have been studied in order to suggest improvements, e.g. on sensitivity factors, which may result in an enhanced detection of tampering and malfunctions. Study on other user behaviours, given by technicians, garages and tuning centres on poor maintenance or tampering has been conducted, taking into account the real effectiveness of OBD and periodic inspections. Additionally, an in-depth analysis of the vehicle inspection data has been performed with data provided from Turkey, Finland and Spain. By analysing Periodic Technical Inspection (PTI) data, one might conclude that a year-on-year increase in random emission checks (leading to a greater number of penalties being issued for violations), has a positive effect on reducing emission failures. Also, overloading of trucks and buses may be one of the reasons for increased failure percentages. More specific controls and higher penalties for overloading would help combat this.

Two options for vehicle modification and/or manipulation were studied: Engine Control Unit (ECU) reprogramming and/or tampering of the vehicle Engine After-Treatment System (EATS). The results acquired from this demonstration suggests that the effect of different ECU remapping and EATS tampering solutions may change the vehicle performance characteristics relatively significantly. The ECU reprogramming versions adapted in this study were found to affect especially the EATS thermal control, increasing the delay of catalyst activation. No effect on particulates was found for ECU reprogramming with the Diesel Particulate Filter (DPF) installed. On contrary, removal of vehicle EATS neglects totally the suppression of any exhaust pollutants, resulting in exhaust emissions which correspond to engine raw emissions.

Necessary software has been created and demonstrated for passenger cars. The software combines EOBD codes that indicate potential tampering violations or improper maintenance. The proposed system can be a multiple actor, to: allow predictive maintenance so that the necessary precautions can be taken as to encourage drivers to intervene; inform the periodic inspection technician that an irregular vehicle behaviour is spotted that might lead to tampering or improper maintenance; transfer the fault codes through IoT to a central database to discourage tampering and assess the vehicle maintenance levels.

Besides the above technical aspects, an overview of best practices and recommendations based on the legal research (from MODALES WP2, above) was carried out on vehicle tampering. Analysis of the current situation provided evidence of the need to strengthen regulations and monitoring processes. Regulatory improvements for more rigorous inspection controls all over Europe, together with a tougher sanction system for both vehicle owners and technician violators have been discussed. The recommendations also suggest that Member States may consider applying rules outside the context of the type approval process in order to prohibit a wider scope of tampering conducts.

3. Potential impact

The Impact Assessment work in MODALES (WP6, D6.4) focused on assessing the impact and effectiveness of the innovative solutions proposed by MODALES. It analysed the data collected locally within MODALES trials in order to quantify the emission reductions achieved at the national scale in four of countries where MODALES trial sites were located (in Finland, Italy, Spain and Turkey) and two other large European countries (Germany and France).

The evaluation takes into account both quantitative data, such as emission measurements, fuel consumption, and maintenance records, and qualitative feedback from participants. In addition, the deliverable discusses the challenges and lessons learned during the evaluation process and identifies areas for improvement or further research.

MODALES developed innovation solutions to address the complex issues explained above, that are divided into four main areas: drivers and their driving behaviour, retrofits that enable emissions to be reduced, the EOBD that enables to malfunctioning to be notified, and inspections to detect poorly maintained and tampered vehicles.

The innovation solutions from MODALES could be transformed into practical solutions, ready to be implemented by countries in Europe and beyond. All these forms of actions should affect direct or indirect emissions, but through different process. From the detailed technical studies from MODALES partners, and from studies about European national regulations, three main practical solutions are proposed, and their potential impacts tested through scenarios built upon MODALES trial tests and studies results.

3.1. Regulation policy to detect poorly maintained and tampered vehicles

This solution can be summarised by the two following measures.

- Mandatory tampering detection using OBD data during the periodic inspections
- Penalties to vehicle owners when a manipulation of the vehicle data by an aftermarket software is detected.

A tampered vehicle can be repaired once detected, which reduces by 80% the NO_X and PM emissions. The impact of this solution is estimated based on assumptions about the average tampered vehicle prevalence in the fleet (MODALES result & literature review), and about the detection rate (lower and upper values based on MODALES lab experiments).

3.2. Retrofits

The second solution is to generalise retrofits for diesels whenever it is possible and relevant. MODALES lab tests proved that retrofitted vehicles could save up to 70% of NOx emissions, and more than 90% of the PMs.

The impact of this solution is done by estimating the proportion of vehicles for which retrofit is relevant based on MODALES cost benefits analyses (ref).

3.3. MODALES Smartphone app

The third solution is the mobile app for low-emission driving that aims to assist drivers throughout their journeys by providing recommendations that do not interfere with their driving. The feedback allows drivers to learn from bad driving habits and improve their emissions reduction. Together with online training videos, supported by an awareness campaign with low-emission driving tips, the app is capable of impacting driving style and generating benefits on pollutant emissions.

The combined impact of the app and the training was evaluated through the experimental and large-scale trial tests results conducted within MODALES.

The methodology for Impact assessment is based on the COPERT software, which is used to compare baseline vehicle emissions for some European countries (Finland, Italy, Spain, Turkey, Germany, and France) with the estimated emissions after the implementation of MODALES solutions. It specifically measures the emission savings by estimating air pollutant emissions and greenhouse gas emissions from road vehicles for the following pollutants: CO2, CO, NOx, and PM.

3.4. Overview of the MODALES solutions and extrapolated impacts

The following figure gives a summary of the expected impacts of the three main innovation solutions of MODALES: A maintenance and tampering detection measure, retrofits, and the app + training.

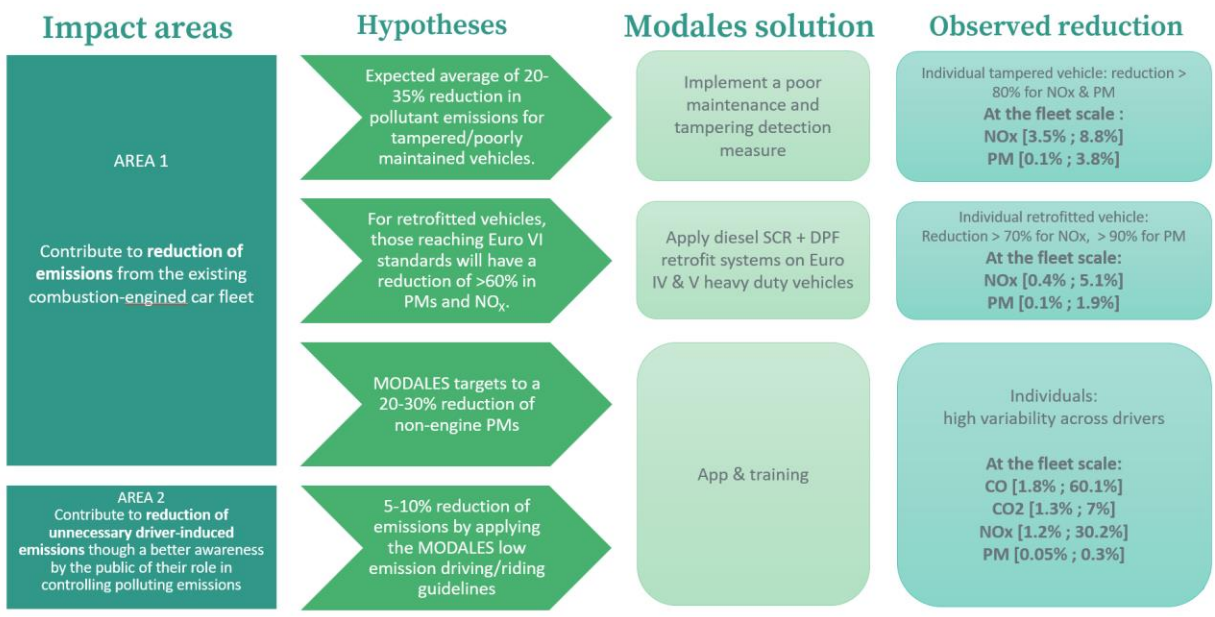

Figure 20: Overview of the MODALES solutions and their extrapolated impacts at the European country level

For each Innovation Solution, assumptions are made based on literature survey or MODALES results and experts' knowledge. These assumptions are used to build different scenarios. First, a "lower" scenario is built based on a pessimistic assumption, then an optimistic scenario is built and called "upper". These scenarios are then translated into a set of quantitative assumptions on the emissions that are suitable to be used as an input parameter into COPERT software.

The baseline performances are estimated using the evolution of the vehicles fleet share across Euro standards for each studied country. A simple reconstruction method is proposed: Eurostat data is used to rebuild the share of Euro standards starting from year 2010, up to the year 2021. Missing data are extrapolated linearly when necessary, and the future evolution of the stock until 2025 is estimated by extending the linear trend over the years 2018, 2019, 2020, 2021.

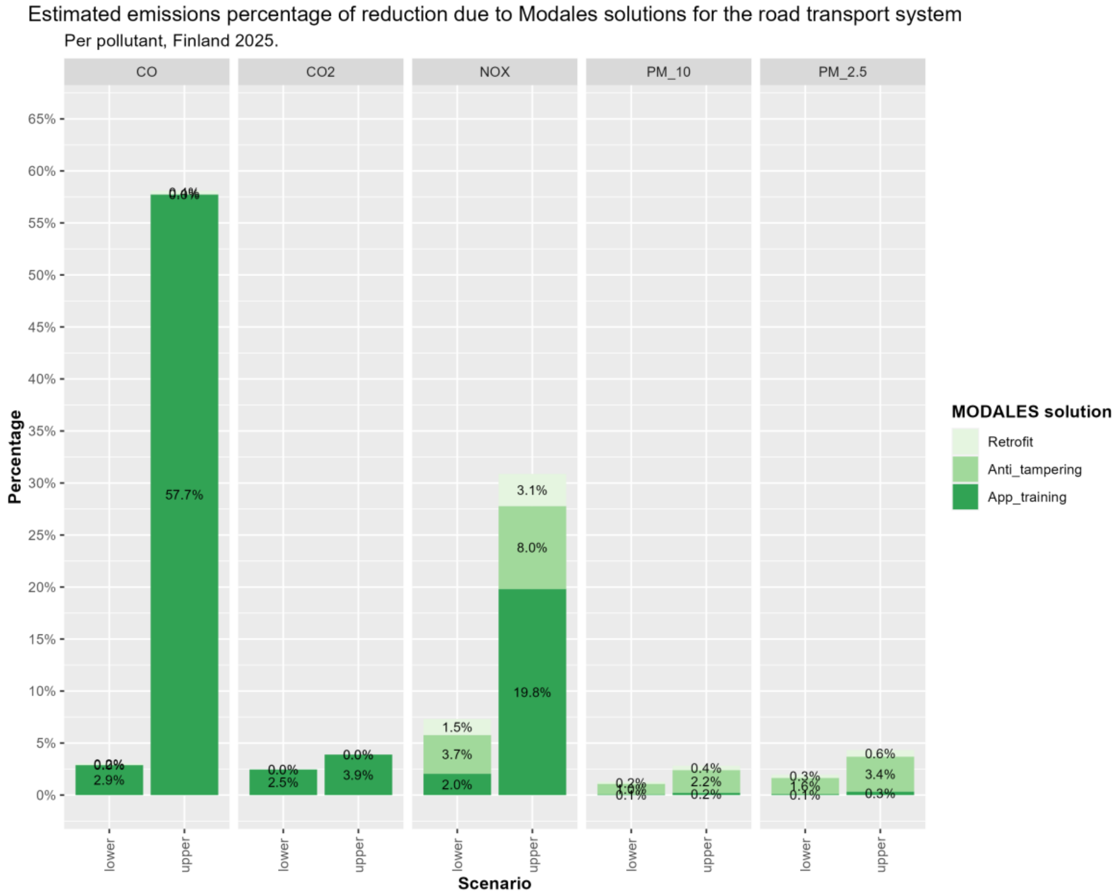

Figure 21: Estimated reduction of pollutants for year 2025 according to the scenario and the MODALES solutions: Example of Finland

Results showed that the older the vehicle stock, the more savings can be expected from the MODALES proposed solutions. This is because older vehicles are often less fuel efficient and emit more pollutants than newer models. By retrofitting these vehicles with newer technology and implementing anti-tampering measures, emissions can be reduced and fuel efficiency can be significantly improved at the country level.

However, the effectiveness of these measures varies depending on the type of vehicle and the country in question. For example, countries with older vehicle stocks may see greater benefits from retrofit campaigns, while countries with newer stocks may see limited or no impact. Similarly, the potential savings from anti-tampering measures may be greater in some countries than in others.

Results also shows that there is significant potential for savings through app-based solutions and training programmes that encourage more efficient driving. However, these solutions may not be as effective as OEM embedded systems, which are typically more expensive but also more efficient, particularly on the long term.

Overall, the research suggests that there is significant potential for reducing emissions in the transportation sector through a combination of anti-tampering measures, retrofit campaigns, and behaviour-related changes. However, the effectiveness of these measures will depend on a variety of factors, including the type of vehicle, the country in question, and the specific technology used. As such, a targeted and nuanced approach will be necessary to achieve meaningful reductions in emissions.

4. Project communications (including website)

4.1. Overview

The main elements of the dissemination process in MODALES have been:

- The Dissemination Strategy, including MODALES dissemination objectives target groups and key messages to provide consortium partners with a set of useful guidelines to plan and perform dissemination activities, with the final aim to ensure a correct process for the dissemination of project results.
- Communication tools and techniques, including development of the visual identity and branding of the project, the project website as main dissemination tool and other materials.
- Media (including a promotional video) and articles.
- Conferences and events, including the MODALES Mid-term and Final Conferences.
- Key Performance Indicators (KPIs) for the MODALES dissemination and communication strategy as well as a reporting process.

In addition, an Awareness Campaign was included as a specific task in this Work Package(described under section 2.1), aimed at end users (drivers of cars, light and heavy commercial vehicles) but also as a tool for motoring organisations, public authorities, driving schools, fleet operators, etc.

Completed actions include the update of the website's library section, including public deliverables, publications, and press clippings, as well as regular news and events articles, a 1.5 minute promotional video (https://www.youtube.com/watch?v=A0N80RQ5LDQ&t=3s), the publication of the MODALES factsheets with the final results in each key area, and the organisation of the MODALES Mid-term webinar and Final Conference.

MODALES fulfilled its requirements in terms of dissemination and communication, reaching most of its final KPIs despite the effect of the COVID-19 pandemic, which made it difficult to organise or attend physical meetings and events in 2020 and 2021. The project had the opportunity to be presented at numerous physical events since the ITS World Congress in October 2021, which was the first face-to-face event since the outbreak of the COVID-19 pandemic.

4.2. Technical dissemination

One of the key goals of the technical dissemination was to submit publications of project results in conference proceedings and peer-reviewed scientific journals. During the period of the project, 17 scientific publications have been submitted and accepted (see Table 2 below). In addition, at least two further publications are expected beyond the project end date.

Table 2: Peer-reviewed scientific publications incorporating MODALES project results

Title	Authors	Partners involved	Journal
Fuel economy and exhaust emissions of a diesel vehicle under real traffic conditions	Jianbing Gao, Haibo Chen, Kaushali Dave, Junyan Chen, Dongyao Jia	LEEDS	Energy Science & Engineering (Gold access)
Analysis of Driving behaviours of truck drivers using motorway tests	Jianbing Gao, Haibo Chen, Kaushali Dave, Junyan	LEEDS, DYNN, SEU	Proceedings of the Institution of Mechanical Engineers, Part D: Journal

Title	Authors	Partners involved	Journal
	Chen, Ying Li, Tiezhu Li, Biao Liang		of Automobile Engineering (Green access)
The effect of after-treatment techniques on the correlations between driving behaviours and NOx emissions of passenger cars	Jianbing Gao, Haibo Chen, Ye Liu	LEEDS	Journal of Cleaner Production
Evaluation of the oxidative reactivity and electrical properties of soot particles	Ye Liu, Chonglin Song, Gang Lv, Wei Zhang, Haibo Chen	LEEDS	Carbon
Comparative analysis of non-exhaust airborne particles from electric and internal combustion engine vehicles	Ye Liu, Haibo Chen, Jianbing GaoJ, Ying Li, Kaushali Dave, Junyan Chen, Matteo Federici, Guido Perricone	LEEDS, DYNN, BREMBO	Journal of Hazardous Materials
Thermally induced variations in the nanostructure and reactivity of soot particles emitted from a diesel engine	Ye Liu, C Fan, X Wang, F Liu, Haibo Chen	LEEDS	Chemosphere
Comparison of NOx and PN emissions between Euro 6 petrol and diesel passenger cars under real-world driving conditions	Jianbing Gao, Haibo Chen, Ye Liu, Juhani Laurikko, Ying Li, T Li & R Tu	LEEDS, VTT, DYNN	Science of the Total Environment
A Survey of In-Vehicle Monitoring Solutions for Low-Emission Driving	Sébastien Faye, Neamah Al-Naffakh, Uwe Roth, Christian Moll, Dimitris Margaritis	LIST, CERTH	ACM Computing Surveys
Impacts of De-NOx system layouts of a diesel passenger car on exhaust emission factors and monetary penalty	Jianbing Gao, Haibo Chen, Ye Liu, Ying Li	LEEDS, DYNN	Energy Science & Engineering
The effect of nonlinear charging function and line change constraints on electric bus scheduling	A Zhang, T Li, R Tu, C Dong, H Chen, J Gao, Y Liu	LEEDS	Promet – Traffic & Transportation
Driving behavior oriented torque demand regulation for electric vehicles with single pedal driving	Y Zhang, Y Huang, H Chen, X Na, Z Chen, Y Liu	LEEDS	Energy
“Monetary values of exhaust and non-exhaust emissions emitted from conventional and electric vehicles	Y Liu, H Chen H et al	LEEDS	Journal of Cleaner Production (Elsevier)
Comparisons of NOx, PM, and PN emissions from Euro-6 compliant petrol and diesel	Jianbing Gao, Haibo Chen, Ye Liu et al	LEEDS	Science of the Total Environment

Title	Authors	Partners involved	Journal
passenger cars under real-world driving conditions			
An Enhanced Predictive Cruise Control System Design with Data-driven Traffic Prediction	Dongyao Jia, Haibo Chen, Zuduo Zheng, David Watling, Richard Connors, Ying Li	LEEDS, DYNN	IEEE Transactions on ITS
PM10 prediction for brake wear of passenger car during different test driving cycles	Ye Liu, Haibo Chen, Chuhan Yin, Matteo Federici, Guido Perricone, Ying Li, Dimitris Margaritis, Yang Shen, Junhua Guo, Tangjian Wei	LEEDS, BREMBO, DYNN, CERTH	Chemosphere (Elsevier)
Impact of vehicle type, tyre feature and driving behaviour on tyre wear under real-world driving conditions	Ye Liu, Haibo Chen, Sijin Wu, Jianbing Gao, Ying Li, Zihao An, Baohua Mao, Ran Tu, Tiezhu Li	LEEDS, DYNN, SEU	Science of the Total Environment (Elsevier)
Brake wear induced PM10 emissions during the world harmonised light-duty vehicle test procedure-brake cycle	Ye Liu, Sijin Wu, Haibo Chen, Matteo Federici, Guido Perricone, Ying Li, Gang Lv, Said Munir, Zhiwen Luo, Baohua Mao	LEEDS, BREMBO, DYNN	Journal of Cleaner Production (Elsevier)

Eleven technical papers at conferences (physical and online) were also accepted, as follows (Table 3):

Table 3: Technical papers presented at Conferences

Title	Authors	Partners involved	Conference
An approach for scaling up vehicle fuel and exhaust emission reduction across European motorways	Jianbing Gao; Haibo Chen; Kaushali Dave; Junyan Chen; Jo-Ann Pattinson	LEEDS	ITS European Congress (online), November 2020
Estimating Emissions from Non-road Construction Machineries and Its Uncertainty Analysis: A Case Study in Nanjing, China	Tiezhu Li, Chunsheng Meng, Ran Tu, Yisong Xie, Fangjian Xie, Feng Yang, Haibo Chen, Ying Li, Jianbing Gao	SEU, LEEDS, DYNN	TAP Conference (Graz and online), March 2021
A New Simulation Approach of Estimating the Real-World Vehicle Performance	Jianbing Gao, Haibo Chen, Junyan Chen, Kaushali Dave	LEEDS	SAE WCX digital summit (online), April 2021
An exact algorithm for efficient online optimization of HGV path, speed profile and stops for minimising fuel consumption and emissions under time-varying conditions	Richard Connors, David Watling, Haibo Chen	LEEDS	hEART conference (Lyon and online), April 2021.

Title	Authors	Partners involved	Conference
Low-Emission Driving Assistants: Experience from MODALES	Ramiro Camino, Sébastien Faye, Nikos Dimokas, Dimitris Margaritis	LIST, CERTH	ITS European Congress (Toulouse), May 2022
Influence of the driving behaviour on the non-exhaust brake emission	Matteo Federici, Mara Leonardi, Andrea Bonfanti, Guido Perricone	BREMBO	Eurobrake (online), May 2022
Integrative Emissions and Health-Based Scoring Algorithm Development for Driving Style Optimization	Engin Özatay, Orhan Alankuş	OKAN	ITS European Congress (Lisbon), May 2023
Information System for Vehicle Anti-tampering based on OBD Data	Nikos Dimokas, Dimitris Margaritis, Andrew Winder	CERTH, ERTICO	ITS European Congress (Lisbon), May 2023
Multi-objective speed profile optimisation considering fuel and NOx	Zhiyuan Lin	LEEDS	ITS European Congress (Lisbon), May 2023[1]
Recognition of Low-energy Consumption Driving Behavior of Electric Bus based on Machine Learning	T. Liu, Q. Han, T. Li, Haibo Chen, Ying Li, J. Sun	SEU, LEEDS, DYNN	23rd COTA (Chinese Overseas Transportation Association) International Conference of Transportation Professionals (Beijing), July 2023[2]
Construction of NOx emission states identification method of diesel bus based on judgment matrix: A case study of Nanjing	Z. Liu, T. Li, H. Chen, Y. Li	SEU, DYNN, LEEDS	ITS World Congress (Suzhou, China), October 2023

In addition to the technical and scientific papers listed above, MODALES has presented at the following 16 external events (physical or live online):

- European TRWP (Tyre and Road Wear Particles) Platform in Brussels, February 2020 (BRIDGESTONE & ERTICO)
- Interdisciplinary online congress on driver training, Greece, May 2020 (CERTH)
- Effie Mobility Online event, Spain, November 2020 (ERTICO)
- ITS Spain Congress in Madrid, July 2021 (ACASA)
- Summer School in Nanjing, China, July 2021 (DYNN, SEU)
- ITS World Congress in Hamburg, October 2021: Special Interest Session "Intelligent systems to help drivers and road authorities reduce pollutant emissions: Beyond eco-driving" (ERTICO, LEEDS) and project panel/screen at ERTICO stand
- EU H2020 Road Transport Research Results (RTR) Conference in Brussels, March 2022 (ERTICO)

[1] Paper accepted and published in Congress proceedings, but not physically presented at the event
[2] Conference upcoming at the time of writing this report, but the paper has been accepted

- ITS European Congress in Toulouse, May-June 2022: Special Interest Session "How can green driving solutions contribute to Clean Air Policies?" (ERTICO, LIST, CEREMA) and project panel/screen at ERTICO stand
- Eurobrake (online), May 2022 (BREMBO)
- Summer School in Nanjing, China, July-August 2022 (DYNN, SEU)
- Conference on Sustainable Urban Mobility (CSUM), Skiathos, Greece, August-September 2022 (CERTH)
- International final of FIA Region I Best Young Driver Contests in Madrid, October 2022 (FIA)
- DIAS project Final Event in Brussels, October 2022 (ERTICO, SPARK)
- Transport Research Arena in Lisbon, November 2022: Invited Session "Reduction of transport impact on air quality" (ERTICO)
- EU Road Transport Research Results (RTR) Conference in Brussels, February 2023 (ERTICO)
- ITS European Congress in Lisbon, May 2023: Special Interest Session "ITS to mitigate climate change and reduce pollution: Impacts and quick wins" (ERTICO) and project panel/screen at ERTICO stand.

Figure 22: MODALES stand at the ITS European Congress 2022, Toulouse

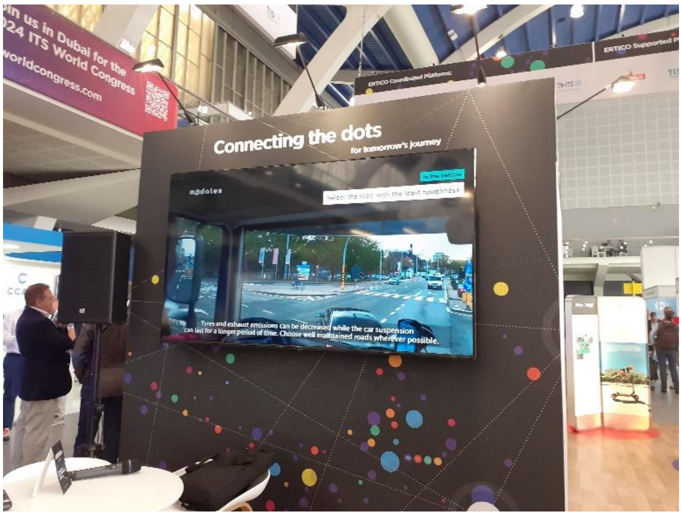

Figure 23: MODALES training video being shown in the Exhibition area of the ITS European Congress 2023, Lisbon

MODALES held a **Mid-term Conference** as an online webinar during Year 2, in May 2021 and reported on the project's current progress and outcomes to date, as well as expected final outcomes. This gathered 46 attendees and was summarised in a report, made available publicly on the MODALES website and social media channels, together with the recording of the event and the presentations[3].

The MODALES **Final Conference** took place physically in Brussels in May 2023 and promoted the results, recommendations, and achievements of the project. This gathered almost 40 attendees and

[3] Report and presentations available at https://modales-project.eu/modales-reveals-its-latest-strategy-on-how-to-lower-driving-related-emissions

an article[4] was published on the MODALES website to summarise the main discussion points of the event and make the presentations publicly available.

4.3. Website

The MODALES website was launched in November 2019. The website was published on behalf of the MODALES consortium in order to disseminate the project activities and to serve as an interaction platform for project relevant data and information. The website presents the work of the MODALES project partners and stakeholders, as well as latest news and events.

The project website can be found at www.modales-project.eu

From 1 September 2020 to 31 August 2021, monthly visits to the MODALES website were on average 322 per month, which meets the KPI for the second year of 200 visitors per month.

The most visited pages were the news and events page, followed by the "About" and deliverables page.

From 1 September 2021 to 31 May 2023, monthly visits to the MODALES website were on average 269 per month, which meets the KPI for Years 3 and 4 of 250 visitors per month.

The most visited pages were the News & Events, "About" page, the English page of the Awareness Campaign ("Check out our simple tips to reduce your driving emissions"), and the deliverables page.

In 2022, a new section of the website was created for the Awareness Campaign of the project, with eleven sub-pages gathering tips to reduce driving emissions in eleven different languages. The English page of this new section of the website was the most visited, followed by the tips in Catalan, German, and Italian.

All public deliverables, videos and technical/scientific papers are available on the website, which will be maintained for three years after the project close (i.e. at least up to the end of May 2026).

4.4. Social media

Twitter/X has been used as a channel to promote "live" news, especially related to project events and results. In addition, this channel has been used as reflector of the website's news and news/information by project partners. The consortium used existing channels of project partners[5] and promoted MODALES using the hashtags #MODALES, #MODALES4cleanmobility, #MODALESproject, and #MODALEStips. The KPI set for Years 3 and 4 of 200 posts related to MODALES was reached with a total of 279 tweets citing #MODALESproject and #MODALEStips.

The promotional video on YouTube (https://www.youtube.com/watch?v=A0N80RQ5LDQ&t=3s), also accessible via the media section of the project's website and promoted on Twitter and LinkedIn, as well as in events, has received 202 views, while the training videos on YouTube (all language versions together) have received over 900 views.

A MODALES LinkedIn group was established early in the project by the Project Coordinator. The purpose of the group is to share project information and news and to establish a community relevant

[4] Summary article of the Final Conference, including presentations, available here: https://modales-project.eu/modales-final-conference-project-wrap-up-marks-a-key-milestone-on-the-road-to-greener-driving/

[5] For example ERTICO (@ertico, over 8000 followers), RACC/ACASA (@ClubRACC, over 60 000 followers), IRU (@the_IRU, over 9000 followers), FIA Region 1 (@FIARegionI, over 2000 followers) and LIST (@LIST_Luxembourg, over 4500 followers)

to the project. The group is accessible via this link: https://www.linkedin.com/groups/12287962/ . The group has 103 members.

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Adapting driver behaviour for lower emissions

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 815189.