Adapting driver behaviour for lower emissions

MODALES D5.1:
Guidelines for low-emission driving

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List of abbreviations and acronyms

MODALES partners and other organisations

Abbreviation	Full partner name
ACASA	Automòbil Club Assistència SAU *(MODALES WP6 leader and an operating company of RACC)*
ACEA	Association des Constructeurs Européens d'Automobiles / European Automobile Manufacturers Association
BREMBO	Freni Brembo SpA *(MODALES partner)*
BRIDG	Bridgestone Europe NV/SA *(MODALES partner)*
CEREMA	Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement *(MODALES partner)*
CERTH	Centre for Research and Technology Hellas / Ethniko Kentro Erevnas kai Technologikis Anaptyxis *(MODALES partner)*
EC	European Commission
ERTICO	ERTICO – ITS Europe *(MODALES project coordinator)*
FIA	Fédération Internationale de l'Automobile *(MODALES partner)*
INEA	Innovation and Networks Executive Agency *(agency of the European Commission)*
IRU	International Road Transport Union *(MODALES partner)*
LEEDS	University of Leeds *(MODALES partner)*
LIST	Luxembourg Institute of Science and Technology *(MODALES partner)*
MICH	Manufacture Française des Pneumatiques Michelin *(MODALES partner)*
OKAN	Istanbul Okan University / İstanbul Okan Üniversitesi *(MODALES partner)*
PROV	Proventia Oy *(MODALES partner)*
RACC	Real Automòbil Club de Catalunya / Royal Automobile Club of Catalonia *(Owner organisation of ACASA)*
SPARK	Spark Legal Network (EU) BVBA *(MODALES partner)*
TRL	Transport Research Laboratory Ltd. *(UK)*
VTT	Technical Research Centre of Finland Ltd / Teknologian Tutkimuskeskus VTT Oy *(MODALES partner)*

General abbreviations and acronyms

Abbreviation	Meaning
AS	Accelerating Sharply
BM	Braking Moderately
BRK	Brake pedal pressure
CMT	Core Management Team
DALED	Driver Assistance app for Low-Emission Driving
DPF	Diesel particulate filter
DS	Decelerating Sharply

Abbreviation	Meaning
DT	Decision Tree
EATS	Exhaust After-Treatment System
ECU	Electronic Control Unit
EGR	Exhaust gas recirculation
EOBD	European On-Board Diagnostics
EU	European Union
F. ACC.	Frontal acceleration
FP7	Seventh Framework Programme
GAS	Gas pedal position
HDV	Heavy Duty Vehicle
HS	Cruising with Higher Speed
I/M	Inspection and Maintenance
ICT	Information and Communication Technologies
IS	Innovation Solutions
ITS	Intelligent Transport System
KPI	Key Performance Indicator
L. ACC.	Lateral acceleration
LA	Long-Time Accelerating
LI	Long-Time Idling
LR	Logistic Regression
LS	Running with Low Speed
MooC	Massive Open Online Course
NB	Naïve Bayes Model
NRMM	Non-Road Mobile Machinery
OBD	On-Board device
OED	Optimum Emission Driving
OEM	Original Equipment Manufacturer
PEMS	Portable Emissions Measurement System
PKE	Positive Kinetic Energy
PTI	Periodic Technical Inspection
R.P.M.	Revolutions per minute
RCS	Relative Cubic Speed
RF	Random Forest
RMSA	Root Mean Square of Acceleration
ROI	Return on Investment
RPA	Relative Positive Acceleration
RPCS	Relative Positive Cubic Speed
RPS	Relative Positive Speed

Abbreviation	Meaning
RPSS	Relative Positive Square Speed
RRCS	Relative Real Cubic Speed
RRS	Relative Real Speed
RRSS	Relative Real Square Speed
RSS	Relative Square Speed
S.W.A.	Steering wheel angle
S.W.M.	Steering wheel momentum
SM	Starting Moderately
SoA	State of the Art
SPD	Speed
SS	Frequently Stop and Start
THC	The Human Condition
URL	Uniform Resource Locator
US	United States
v.a.	Velocity multiplied by acceleration
VSP	Vehicle Specific Power
WP	Work Package

Executive Summary

The MODALES project works towards reducing air pollution from all types of on-road vehicles by encouraging adoption of low-emission driving behaviour and proper maintenance choice. This deliverable is part of Work Package 5 - Guidelines & Tools for Low Emission Training, which is one of the five technical Work Packages of MODALES.

This deliverable is the result of Task 5.1. - Guidelines for Low Emission training, which aims to ensure the link between the theoretical aspects of the project and their validation and use during the experimentation phase (WP6) and awareness campaigns (WP7). To do so, WP5 considers the results of all the WPs mentioned above, with the aim of *(a)* defining guidelines for low-emission driving and *(b)* defining tools to monitor and improve driving behaviour resulting in emission losses.

In this context, a mobile app is developed as a Driver Assistance app for Low-Emission Driving (current working name: DALED). It will be complemented by a web dashboard addressed to public and local authorities, providing them with a statistical overview of the data collected from users. Thus, the content of this Deliverable is the base of knowledge for developing the App and the recommendations it will send to their users. Also, the guidelines will be used as input for training courses, which will be designed to ensure a consistency with existing learning processes and serve as input for on-road trials and awareness campaigns.

Similarly, the content of this deliverable is intended to be used as a primary source of knowledge by any entity that wants to develop a tool of any kind to promote low emissions driving: driving schools, environmental agencies, IT companies and App developers, transport associations, etc.

In order to identify the guidelines, the first step was to determine the effect of different driving styles under different environmental and road conditions on emissions. This analysis was carried out in MODALES WP2, which focused on the definition of different deriving styles and their effect on tailpipe, brake and tyre emissions.

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:

Powertrain emissions while driving

- 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.

Brake emissions while driving

- 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 high 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.

Tyre emissions while driving

Using the results of the literature survey (see MODALES Deliverable 2.1, Chapter 5 Tyre Wear) the following guide lines can be outlined: (Guideline – Qualitative/Quantitative – Impact: 1. High 2. Medium 3. Low)

Environment - Route:

- Use Correct Season Tyres (Summer - Winter - A/S) – Qualitative – 2
- Select Route with low slope and/or higher straight line – Qualitative – 2
- Select Route with Lower Traffic (at comparable distance) – Qualitative - 2
- In case of available road characteristic info select road with low micro-roughness - - Qualitative – 2

Vehicles:

- Monitor / Keep correct tyre pressure – Qualitative - 2
- Control Tyre Wear Profile (Visual inspection) and assure proper Static Setting – Qualitative - 1
- Avoid overload or un-necessary weight transportation – Qualitative – 1
- Select Eco-driving mode option (when available) – Qualitative – 3

- For Electrical Vehicles optimise Equilibrium between Battery Regeneration and Tyre Wear – Qualitative – 2

Usage:

- Avoid high acceleration/deceleration both Transversal and Longitudinal – Quantitative – 1
- Reduce car (use alternative mobility solutions) usage in case of short Time (Thermal state of Tyre) – Qualitative – 3
- Tyre position rotation – Qualitative - 3

Maintenance, pre-driving checks and tampering aspects

- 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.

Finally, this deliverable includes an initial exploitation plan. The exploitation activities include the creation of the DALED app that will send recommendations to users, but also the main action lines for awareness and dissemination campaigns and the audience towards which each action should be directed.

1. Introduction

1.1. Project overview

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

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

MODALES aims to modify user (driver) behaviour via dedicated training including a driver assistance app and awareness campaigns to support effective air quality improvement plans and enforcement strategies to be developed by local and national authorities.

To achieve this goal, MODALES researches, develops and tests 13 innovation solutions (IS), of which 11 are technical innovations, in order to substantially reduce vehicle emissions from the main sources given above, for passenger cars, light and heavy-duty vehicles (buses and trucks) and Non-Road Mobile Machinery (NRMM).

The main activities of MODALES are:

- 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 one-year long low-emission user trials (with both driving and maintenance practices), supported by awareness campaigns, to enhance public engagement and help drivers better understand the impact of their driving and maintenance behaviours in all situations.

1.2. Scope of the document and relation to other tasks

This deliverable is part of Work Package (WP) 5 on **Guidelines and Tools for Low-Emission Driving**, which is one of the five technical WPs of MODALES (the two "non-technical" WPs include WP1 on Project Management and WP7 on Awareness, Communication and Dissemination). The other four "technical" WPs that are directly connected with WP5 are the following:

- **WP2: Defining low-emission factors**, which explored driving behaviour variability using existing available data, as well as a data collection campaign using an on-board data acquisition setup with access to powertrain data (PEMS measurements - portable emissions measurement system). This WP delivered a first approach on driving behaviour patterns and powertrain emissions. It also addressed the state-of-the-art in retrofits, inspection and maintenance (I/M) and legal issues regarding tampering in various EU Member States. Link with WP5: inputs from T2.1 on Variability of Driving Behaviours and T2.2 on OBD inspection and maintenance requirements are used to develop the guidelines for low emission driving on this deliverable (developed in T5.1) and therefore the mobile app and the trainings (developed in T5.5).

- **WP3: Impact of user behaviours**, which undertakes a series of measurement campaigns to establish the correlation between driving behaviour and powertrain exhaust emissions, as well as fine particulates from brakes and mass-loss from tyres. Measurement campaigns are also carried out to address the impact of poor maintenance and deliberate tampering of the emissions control system. Link with WP5: inputs from T3.5 on Correlation of user behaviour variability with emissions to develop the guidelines and implement part of the profiling methods.
- **WP4: Effectiveness of inspections and depollution systems**, which uses the findings of WPs 2 and 3 as a base to investigate and propose solutions that will contribute to emission monitoring via the EOBD protocol and systems that detect lack of maintenance and tampering. It also investigates the potential of enhancing existing retrofit systems. Link with WP5: inputs from T4.1 on OBD Logging to T5.2 Functional specifications of tools and T5.3 Low-emission driving assistance tools to integrate all the necessary data into the mobile app features and characteristics.
- **WP6: User trials and evaluation,** develops the evaluation plan, the testing and the evaluation with real-world trials for the functionality of the innovations developed in MODALES, their effects on driver acceptance and performance, and their potential wider impact (in particular their predicted overall effects on vehicle emissions). Link with WP5: the mobile app will be used as the main tool for T6.1 – Evaluation Plan, T6.2 on Trial Ramp-Up Pilots, T6.3 on Large Scale user Trials.

1.2.1. Overview of MODALES WP5 on Guidelines and tools for a low-emission training

The first mission of WP5 is to ensure the link between the theoretical aspects of the project and their validation and use for experimentation (WP6) and awareness campaigns (WP7). To do so, WP5 considers the results of all the WPs mentioned above, with the aim of

a) defining guidelines for low-emission driving and

b) defining tools to monitor and improve driving behaviours resulting in emission losses.

In this context, a mobile app will be developed as a Driver Assistance app for Low-Emission Driving (current working name: DALED). It will be complemented by a web dashboard addressed to public and local authorities, providing them with a statistical overview of the data collected in WP6. The DALED will be developed and tested in this WP. Finally, the guidelines defined in this deliverable will be used as input for training courses, which will be designed to ensure consistency with existing learning processes and serve as input for on-road trials and awareness campaigns.

WP5 is broken down into 5 tasks:

- **T5.1 Guidelines for low-emission driving**. Objective: create a reference list of good and bad practices for low-emission driving, their impact and the actions the user could take to improve them.
- **T5.2 Functional specification of tools**. Objective: specify the tools to be developed in T5.3, including: The mobile application and its modules, its operating logic, HMI aspects, the centralised web application.
- **T5.3 Low-emission driving assistance tools**. Objective: develop all the elements specified in T5.2 into advanced prototypes.
- **T5.4 Testing and technical verification of tools**. Objective: test, verify and deploy all the software developed and integrated during the WP. This Task will also calibrate and technically validate the application.
- **T5.5 Developing training for low-emission driving**. Objective: use the guidelines, tools and all the knowledge accumulated in WP5 as an input to design the training courses carried out in WP6. Tailor-made training courses will be derived from guidelines, for various road vehicle users (including junior drivers, taxi drivers, driving schools, etc.), types and configurations of vehicles.

1.2.2. Relation to other MODALES work-packages and deliverables

Figure 1 below shows how this deliverable fits into the project and highlights related deliverables which will take into account the content of this one.

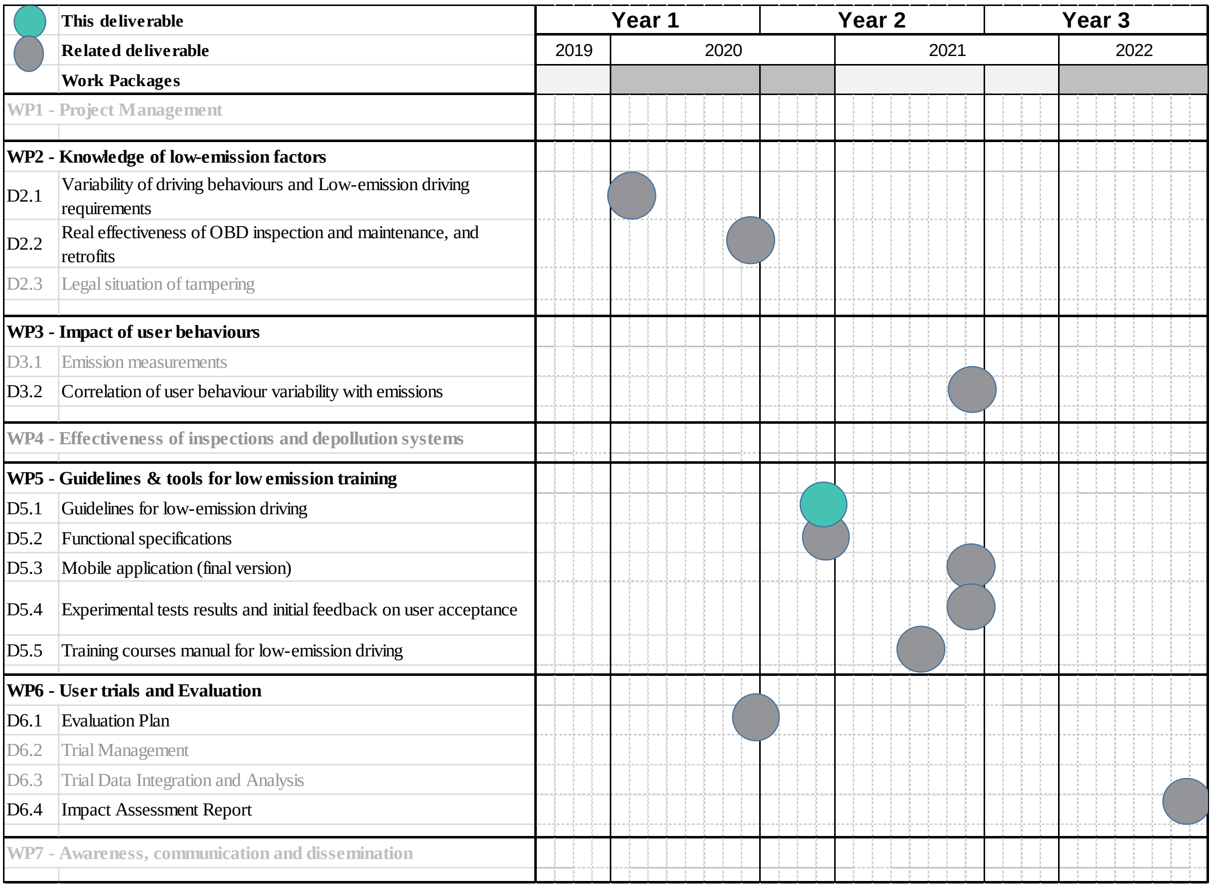

Figure 1: D5.1 Guidelines for low-emission driving in the context of related MODALES deliverables

The present document has been developed in parallel to D5.2 ("Functional Specifications"), which specifies how the project tools will implement the guidelines.

1.2.3. Intended audience of this deliverable

The Guidelines developed in this deliverable come from the knowledge acquired in previous WP on both emission factors and driving behaviour and will be the base of the Low-Emission Trainings that will be developed, as well as the base of the DALED app that will advise drivers for their best driving style depending on the situations and needs. Hence, the content of this deliverable is intended to be used as a primary source of knowledge by any entity that wants to develop a tool of any kind to promote low emissions driving: driving schools, environmental agencies, IT companies and app developers, transport associations, etc.

1.3. Structure of the deliverable

Chapter 2 introduces the approach for the identification of the guidelines with the existing knowledge from past projects and experience gathered in MODALES's technical work packages.

Chapter 3 approaches driving behaviour and a proposed methodology for it evaluation. The proposed methodology includes both a procedure for identification of KPI and a proposal for their scoring. This would enable the MODALES DALED app to give real time recommendations to the driver.

Chapter 4 identifies the guidelines of each type of emissions individually, from power-train emissions to brakes and tyres. A section on guidelines for maintenance and aspects related to tampering is included as MODALES aims to influence user's behaviour on that aspect as well.

Chapter 5 focuses on the possible uses of the knowledge aggregated in the deliverable, as it will be the base for the Trainings and the App the will be developed in MODALES; but could be used for other purposes.

Finally, Chapter 6 summarises the guidelines and provides the list the will be the base for further development in MODALES.

1.4. Description of Action and deviations

1.4.1. Description of Action (DoA)

The description of action includes four action points to be covered by the present deliverable:

- Reference all the conclusions made in the other work packages, notably WP2 and WP3, and convert them into performance indicators to evaluate practices for low-emission driving;
- Create scoring functions to assess each indicator;
- Rank these indicators according to their importance with respect to low-emission driving, and considering several types of engines, brake systems and vehicles.
- Compare these indicators with different types of users, and for each possible combination, identify at least one possible behaviour to adopt in order to improve the indicator scoring.

1.4.2. Content deviations

- This deliverable fulfils the aggregation as it considers the conclusions of the other WPs as a basis for developing the low-emission guidelines in MODALES. However, at the time of writing this document (early December 2020), some test results from WP3 are not yet available due to the COVID-19 pandemic, thus making it impossible at this stage to fully verify some of the conclusions related to the guidelines. As a partial solution to this issue, we have consolidated our analyses by considering results and data from the literature and other projects, so as not to create delays in WP5. The missing conclusions will be elaborated during 2021 in the framework of WP5, during the development of the mobile app and the training courses, and will be described in Deliverables D5.3 and D5.5.
- On the creation of indicators and scoring functions, a methodology is introduced in Section 3.1.
- A ranking on indicators and factors that influence emissions has been done only for tyre emissions. However, factors have been classified as user dependent, environmental dependent or vehicle dependent. The user can act only on those who are user dependent, but the recommendations given will have to consider the others.
- The literature review indicates that aggressive driving is the main behaviour that influences emissions, based on the frequency and intensity of acceleration and breaking. Thus, the focus is on identification those events.

1.4.3. Time Deviations

This deliverable was submitted with approximately two-week delay in mid-December 2020 as some consortium discussions were needed to agree some improvements to the structure and content proposed by the peer reviewers, as well as the approach needed for the missing data and its presentation.

2. Background

2.1. Approach to the development of the guidelines

In order to identify the guidelines, the first step was to determine the effects of different driving styles on emissions, under different environmental and road conditions. This analysis has been made in line with the literature survey carried out in WP2 of MODALES - Knowledge of low-emission factors, and more concretely on MODALES D2.1 – Variability of driving behaviours and low-emission driving requirements, as well as tests and simulations carried out in WP3 on Impact of user behaviour.

2.1.1. Literature review

In WP2 of MODALES, extensive work has been carried out to define different driving styles and, in parallel, the effects of these different driving styles on tailpipe, brake and tyre emissions were investigated. The outcomes of this work are reported in Deliverable 2.1 "Variability of driving behaviours and low-emission driving requirements". Table 7.2 of Deliverable 2.1 gives a list of driving styles related to exhaust emissions, energy consumption and safety. It was seen that all the parameters were related to acceleration, deceleration, speed values and the frequency of accelerations and stops. As a reference, the table is repeated in the Annex to this document.

Also, from the literature survey, a ranking table for driving behaviour with respect to different exhaust emissions have been included. The table shows that speed, acceleration and frequent stops are the most important factors. The table shows the parallel influence of all the emission values as the acceleration changes however speed distribution has more adverse effects on NO_X and PM.

More specific examples were also given in Deliverable 2.1 about the relation between acceleration and speed and emissions. As explained in section 8.2 of deliverable 2.1, high accelerations at low speeds increase tailpipe emissions considerably whereas for no acceleration higher speeds creates more emissions. Therefore, at congested roads, high accelerations causes the emission levels to rise. NO_X can be seen to be more sensitive to velocity.

Driving Dynamics

The Literature review presented in Deliverable 2.1 has been extended to take into account most recent literature and also to deepen the analysis for methodologies to determine the dynamics of driving. Regulation (EU) 2017/1151 describes in Appendix 7a the methodology to determine the driving dynamics. In the annex two parameters were considered mainly. v.a (Velocity multiplied by acceleration) and RPA (Relative Positive Acceleration). Dynamic parameters like acceleration, $v \cdot a_{pos}$

or RPA[1] are required to be determined with a speed signal of an accuracy of 0,1 % for all speed values above 3 km/h and a sampling frequency of 1 Hz.

Kurtykaa and Pielechaa used mainly RPA and v.a under different driving cycles urban, rural and highway and showed different emission results for each cycle even with the same RPA and v.a values.

Zhiqiang et al used speed and acceleration but as a function of VSP (Vehicle Specific Power).

Although Ying Yao et al, mainly estimates the fuel consumption, for driving style determination they use not only velocity and acceleration but also acceleration and deceleration time percentage and cruising time percentage. Table 1 below shows the driving parameters and their calculation used by Ying Yao et al.

Table 1: Driving parameters and their calculation

TABLE 2: Related indexes to predict fuel consumption.

Indicators	Definition	Unit
Average speed V_{mean}	$V_{\text{mean}} = (1/T)\sum_{i=1}^{T} v_i$ where v_i is the speed of i second and T is the total driving time of one day	km/h
Average speed except for idle (ASEI) V'_{mean}	$V'_{\text{mean}} = (1/T')\sum_{i=1}^{T'} v_i$ where T' is the driving time of one day except idle	km/h
Average acceleration $\overline{a}_{+}$	$\overline{a}_{+} = (1/t_a)\sum_{i=1}^{t_a} a_i$ where a_i is the acceleration of i second and t_a is the driving time of acceleration per day	m/s^2
Average deceleration $\overline{a}_{-}$	$\overline{a}_{-} = (1/t_d)\sum_{i=1}^{t_d} a_i$ where t_d is the driving time of deceleration per day	m/s^2
Acceleration time percentage P_a	$P_a = (t_a/T) \cdot 100\%$	%
Deceleration time percentage P_d	$P_d = (t_d/T) \cdot 100\%$	%
Cruising time percentage P_c	$P_c = (t_c/T) \cdot 100\%$ where t_c is the driving time of cruising per day	%
Fuel consumption FC	$\text{FC} = \sum_{i=1}^{T} \text{FC}_i/\text{distance}$ where FC_i is the instantaneous fuel consumption of i second and distance is the total driving distance per day	L/ 100 km

Bodisco and Raze refers to TRL manual and defines driving styles for Euro6 using the kinematic parameters explained in TRL manual.

Analysis of Emissions:

Satlawa et al, using mainly v.a and RPA, comes up with the following results;

For the urban part, (less than 60 km/h) no significant influence of the driver's driving style on instantaneous THC emissions was observed. On the other hand, CO_2 and NO_X emissions significantly increase with the increase of driving dynamics.

1

$$RPA_k = \sum_j \left(\Delta t \cdot \left(v \cdot a_{pos}\right)_{j,k}\right) / \sum_i d_{i,k},$$

$$j = 1\ to\ M_k, i = 1\ to\ N_k, k = u, r, m \qquad (1)$$

where:
RPA_k = relative positive acceleration for urban, rural and motorway shares [m/s^2 or kW·s/(kg·km)]
Δt = a time step equal to 1 second
M_k = the sample number for urban, rural and motorway parts with positive acceleration
N_k = the total number of samples for urban, rural and motorway parts
d_i = the distance covered in time step i [m]
$v \cdot a_{pos}$ = actual vehicle speed-acceleration product [m^2/s^3 or W/kg]

For the rural and motorway parts (over 60 km/h) the instantaneous emission values depended very much on the dynamics of the driving style. CO emissions has increased very rapidly after exceeding the allowed dynamic parameter ($v.a_{pos}$). At cold engine, THC emissions were very high (around 100 times). Dynamic tests were defined with $v.a_{pos}$ values of 15.8; 24 and 29.6 for urban, rural and motorway respectively and with respective RPA values of 0.2292; 0.1071 and 0.0616.

Zai et al, have used VSP (Vehicle Specific Power[2]) windows and related parameters to check the emissions behaviour on CO_2, CO, NO_X and PN. The parameters were engine speed, engine torque, engine load in %, air-fuel ratio, vehicle speed and acceleration, altitude, road grade and road type, catalyst temperature, ambient temperature and time of the day. The paper focuses on documenting the variability in emissions under similar vehicle powers, thus, capturing the effects of other variables clearly. Vehicle emissions are strongly associated with engine speed, torque, and load, as well as air-fuel ratio. The process of high engine speed, torque, and load produces high emissions. The CO_2, CO and PN emissions during lean-burn are significantly lower than the emissions during the stoichiometric mix and rich burn, while the NO_X emissions during rich burn are the lowest. Emissions are also strongly associated with vehicle speed and acceleration. The process of high speed and aggressive acceleration produces high emissions, while the process of braking produces low emissions.

In the same VSP bin, the emissions per second while the vehicle is traveling downhill tend to be higher than the emissions going uphill, because the vehicle is traveling faster and accelerating more frequently when in downhill conditions.

The emissions for restricted access roads (highways) and ramps are higher than the emissions for unrestricted access roads (arterial roads), because of the higher speeds. CO, NO_X, and PN emissions at a low ambient temperature tend to be higher. The emissions in the morning are observed to be higher than the emissions in the afternoon, because of the lower ambient temperature.

For brake and tyre wear, the relation to the driving style can be summarised as follows (Table 2) [13]:

Table 2: Relation to brake and tyre wear to driving style

Driving Features	Brake Wear	Tyre Wear	Road Wear	Resuspension
Aggressive Driving Style	↑	↑	↑	↑
Speed	↑	↑	↑	↑
Acceleration / Deacceleration	↑	↑	?	?
Tyre Pressure		↓	-	-
Wheels imbalance		↑	-	-

Therefore, to take into account brake and tyre wear induced emissions, deceleration magnitude and deceleration frequency becomes important and needed to be detected during driving cycle. This is also in line with the results explained in Sections 3.2 and 3.3 of this deliverable.

2 $VSP = \frac{1}{m}(\frac{d}{dt}(KE + PE) + F_{Rolling} \cdot v + F_{Aerodynamic} \cdot v)$

2.1.2. Past projects and experiences

Training programmes

There is an increasing demand from private companies and public entities to decrease their environmental footprint which leads to the development of targeted eco-driving, fuel efficiency or similar programs. Those training programmes are an easy way to achieve environmentally friendly operations with a low-cost investment and fast returns. Some of the MODALES partners, like IRU have prior experience on the training programmes existing in the market:

Eco-driving by IRU:

Environment and fuel efficiency are top priorities for IRU on both political and research level. The IRU Academy Eco-driving course teaches drivers fuel efficiency techniques, emphasizing on road safety, economy and the environment. Drivers who have been trained on Eco-driving by IRU can increase fuel efficiency by up to 15%.

The course makes drivers aware of road conditions and the impact of their driving style on vehicle efficiency. It shows them how to drive 'eco-efficiently' without losing time.

The Eco-driving benefits achieved after training include:

- Savings in fuel and fleet maintenance
- Lower carbon emissions
- Reduced risks and accidents
- Improved driver performance and awareness.

The Eco-driving training supports key initiatives and regulations on safety, the environment and resource efficiency.

Eco-driving pilots

Through Task 2.4, MODALES partners reviewed different projects, the main results and some other characteristics resulting to Table 3. Related EU funded projects included TREATISE, ECOEFFECT, CIVITAS and ECODRIVEN while several other programs related to transport operators and cities were included. The analysis is included in Deliverable 2.1 of MODALES.

Table 3: Eco-driving pilots and projects (MODALES deliverable 2.1, 2020)

A/A	Project - company	Type of vehicle	Drivers	Tests	Key outcomes and relevance to MODALES	Ref.
1	TREATISE – EU funded (2005-2007)	All types	1722	AT, BE, FI, GR, NL, ES etc. (8 countries in total)	95.000 tonnes CO_2 achieved and 1.011.000 tonnes CO_2 savings forecasted. Results from several large-scale field tests show all devices mentioned save about 5% fuel. Combined with driving style training the benefits are significantly higher.	[1]
2	ECOEFFECT – EU funded (2011-2013)	All types	2500	PO, RO, CZ	5%-9% reduction in fuel consumption - CO_2 emissions by more than 1.000 tonnes and saved 480.000€ in fuel - ROI of 1.323€ per driver per year - Payback in 5 months.	[2]

A/A	Project - company	Type of vehicle	Drivers	Tests	Key outcomes and relevance to MODALES	Ref.
3	CIVITAS eco-driving – EU co-funded (2010)	Buses	274	EE (Tallinn bus company)	Reduced by 3,9% in average for the participants of the training - number of accidents was reduced by 22% - The driving style index was improved by 7,3% in average - drivers awareness on the environment was improved by 29% - B/C ratio 1,567.	[3]
4	Kesko Logistics eco-driving (2012)	Trucks	Not specified	FI & 100 other countries	Average fuel cost saving of 10 to 15 % after one-day eco-driving course.	[4]
5	Comparative effects of eco-driving initiatives aimed at urban bus drivers – Results from a field trial (2013)	Buses	Not specified	Not specified	Examined two programs to develop and maintain ecological bus driving behaviour. A 6.8% fuel saving and large decreases in instances of harsh deceleration and speeding were found. Drivers reported gains in theoretical knowledge, but found it difficult to put that knowledge into practice. Contextual factors were found to limit drivers' to eco-driving.	[5]
6	Eco-driving: pilot evaluation of driving behavior changes among U.S. drivers (2010)	LCVs equipped with eco-driving device	23 light commercial vehicle drivers	South California, USA	This study evaluated how an on-board eco-driving device that provides instantaneous fuel economy feedback affects driving behaviours, and consequently fuel economy, of gasoline-engine vehicle drivers in the U.S. under real-world driving conditions. The results from 23 samples of drivers in Southern California show that on average the fuel economy on city streets improves by 6% while the fuel economy on highways improves by 1%.	[6]
7	Bus eco-driving training (2015)	Buses	29	Several places	Fuel economy for the treatment group improved significantly immediately after the eco-driving training (11.6%) and this improvement was even larger six months after the training (16.9%).	[7]
8	A summary of previous eco-driving training programs (1999-2015)	All types	Not specified	Several - nine eco-driving training programs	Fuel economy of 9.88% on average ranging from 1% to 25%. The review included nine eco-driving training programs.	[8]
9	STIB-MIVB Brussels public transport company (2013)	Buses – public transport	Not specified	BE (Brussels)	5% fuel savings were achieved which would result to 750.000€ in savings if deployed on the whole bus fleet. Payback time of investing in eco-driving equipment and training was estimated to be around two years.	[9]
10	BIELEFELD (MOBIEL) (2013)	Buses – public transport	6	DE (Bielefeld)	This eco-driving programme allowed moBiel to reduce its fuel consumption by 10% (252,000 litres), resulting in a 3.500€ cost saving per bus every year.	[10]

A/A	Project - company	Type of vehicle	Drivers	Tests	Key outcomes and relevance to MODALES	Ref.
					The investment cost reached 1.800€ per training and payback was achieved in approximately 6 months.	
11	ECODRIVEN – EU funded (2006-2010)	All types	Directly and indirectly up to 2.000.000	UK, FR, NL, BE, FI, AT, PL, CZ, GR	Savings immediately post-training are often in the region of 15-20% with long-term savings after training of approximately 10%. Explored the potential of short-duration (snack) training courses, with good results. Reached over 20 million licensed drivers in 9 EU countries and Resulted in 1 Million tonnes CO_2 emission avoidance from 2006 until 2010.	[11]
12	ecoDriver - EU FP7 project (2011-2016)	All types	170 drivers in 6 cities	UK, DE, IT, NL, SE, ES, FR	ecoDriver considered the human element when encouraging "green" driving, as driver behaviour is a critical element in energy efficiency. The focus of the project was on technology working with the driver. The project delivered effective feedback to drivers on green driving by optimising the driver-powertrain-environment feedback loop. 9 different assistance systems for eco-driving – savings of 13% and 20%, depending on how the driver followed the recommendations proposed by the system	[12]
13	optiTruck EU H2020 project (2016-2019)	HDVs	1	Mainly Simulation and also road tests TR,GR,IT	Using environmental, vehicle, map and traffic information optimised velocity profile and powertrain operation point determination gave around 20% fuel saving for a typical transport mission	[21]

The optiTruck example

In the optiTruck project OKAN built the architecture of a real time simulation system and together with IAV and Ford Otosan, the simulation system was verified with road test results for a heavy-duty truck.

A representative schema of the overall system and sub-systems are as shown in the below following figures.

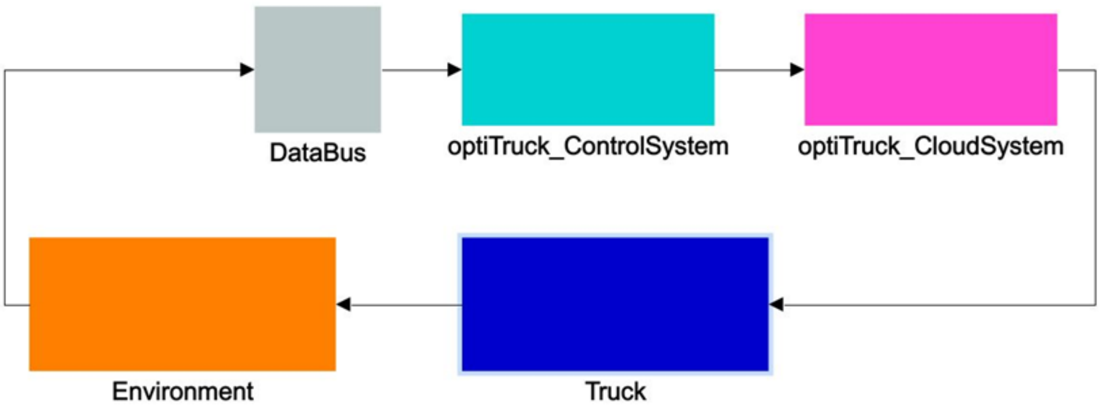

Figure 2: Overall Representation of the Vehicle Simulator Environment (optiTruck project)

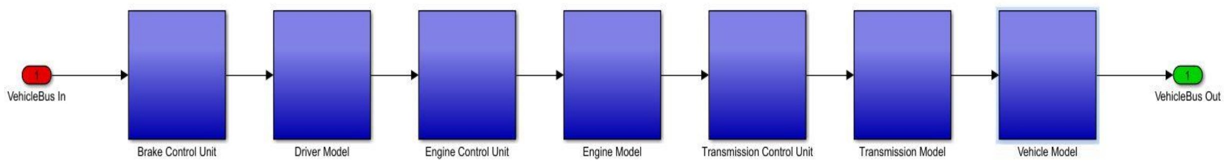

Figure 3: System Level Separation of the functionalities (optiTruck project)

The on-board system has many different functions which are listed hereafter:

a) Engine simulation
b) Transmission simulation
c) Emission estimator
d) Engine operating point estimator
e) Fuel consumption estimator
f) Energy systems simulation
g) Auxiliary systems simulation
h) Longitudinal Vehicle model
i) Radar and camera simulation

For engine and transmission system simulations and related function estimators main systems are GT-SUITE, AVL CRUISE, AVL BOOST, AVL FIRE and RICARDO IGNITE. The systems have similar capabilities. For example, GT-SUITE can simulate engine performance, exhaust after treatment, cooling systems and thermal management, air conditioning and waste heat recovery, transmission simulation, auxiliaries' simulation and fuel consumption calculations.

As seen, most of the functions listed above can be simulated through GT-SUITE. It is important that specific subroutines can be added to GT-SUITE by using programming languages such as C and Matlab. Longitudinal vehicle model and radar and camera simulation exist in most of the vehicle simulations systems. TRUCKMAKER has a built-in predictive cruise control system with radar.

However, such systems are to be ready also for specific subroutine interfaces and insertion and be compatible with Matlab and C programming languages.

Below simulation results obtained for NO_X as a function of speed and velocity are shown. The results are similar to the ones shown on the literature. For HC and CO the results are similar. The objective will be to fine tune the simulation system results for different vehicle types with the PEM results obtained and run several scenarios including road topographic conditions to derive the effect of microscopic driving on emissions and find optimised driving conditions for best conditions of emissions which affect human health.

Obtained results were very much in line with the results shown in the literature. Therefore, this simulation system can be used to verify the algorithms developed for event detection and scoring.

2.1.3. Relevance to MODALES guidelines

The above projects have given input mainly on three areas.

- Driving style attributes and detection
- HMI and the methodology of giving feedback to the driver
- The optiTruck project simulation system is to be used extensively for training of Artificial Intelligence learning algorithm through different driving styles and their effect on emissions. Besides, the simulation system would also be used to verify the guide lines related to tailpipe emissions reductions.

Furthermore, the above projects displayed that there is a need to distinguish real-time and non-real-time driving styles. Thus, two types of recommendations could be produced:

- Active recommendations: Would be given while the driver is actually driving. Those recommendations can only be done by software.
- Passive recommendations: Can be done in very different formats as the user is not driving at the moment they are received. This kind of recommendations would be given, for instance, in training as a post-trip report given by the software.

3. Evaluation of driving behaviour

This section describes how it is possible to assess a user's driving style in real time, i.e. while driving and not necessarily afterwards. It is a necessary basis for any software or application, whether on a phone or embedded in a vehicle, that would need to actively recommend actions to the user - as we would like to do with DALED.

3.1. KPI and Scoring

One way to evaluate a driving style is to calculate a numerical score, in real time, possibly with several dimensions. It has been shown above that v.a and RPA are parameters suggested also in regulation EU 2017/1151 and recent literature shows coherent results with these parameters and emissions. However, converting these results to scoring requires a rigorous methodology. Below a short introduction of the literature for scoring is presented.

Most scoring systems are related to “aggressive driving scoring” as a means of insurance policies.

Abdelrahman et al have developed a methodology for scoring for aggressive driving related to car insurance companies. They have followed the following process for scoring,

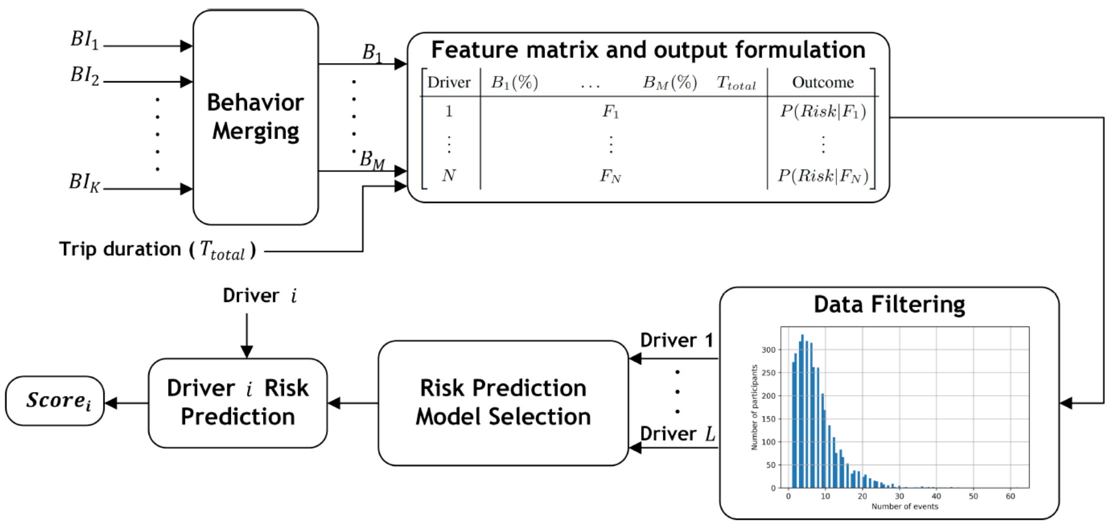

Figure 4: Methodology for scoring for aggressive driving (user for car insurance companies)

Chen et al developed a methodology for scoring and evaluation related to driving behaviour for eco-driving. Although this approach is for eco-driving principles can easily be applied for optimised emission driving. In this study fuel consumption per 100 km is obtained through tests. Nine driving events have been identified which are most relevant to fuel consumption. These are defined as follows,

1) AS (Accelerating Sharply): a(t) > 4 km/h/s
2) DS (Decelerating Sharply): a(t) < 5 km/h/s.
3) LA (Long-Time Accelerating): Ta> 5/s. Accelerating that lasts more than 5s is identified as one LA event.
4) LI (Long-Time Idling): Ti> 60/s. Idling that lasts more than 60s is identified as one LI event.

5) LS (Running with Low Speed). Average speed during 60 seconds is no more than 23 km/h (see (2)), and a period with continuous LSs is identified as one LS event. ave $(s\ (t)\ ,\ s\ (t-1)\ ,\ .\ .\ .\ ,\ s\ (t-59)) \leq$ 23km/h. (2)
6) HS (Cruising with Higher Speed). When driving, during 5 seconds, one has the following:
   (i) Average speed is no less than 60 km/h;
   (ii) Instantaneous acceleration is no more than 1 km/h;
   (iii) Speed standard deviation is no more than 1.5 km/h;
   (iv) Speed variation is no more than 1 km/h;
   (v) A period with continuous HS is identified as one HS event. ave $(s\ (t)\ ,\ s\ (t-1)\ ,\ s\ (t-2)\ ,\ s\ (t-3)\ ,\ s\ (t-4)) \geq$ 60km/h
7) SM (Starting Moderately). When vehicle accelerates from idling, during 5 seconds, one has the following:
   (i) Speed variation ∈ [10, 20] km/h/s; see (7)
   (ii) Product of driving mode codes equals 1 or 3; see (8)
   (iii) Maximum acceleration is no more than 4 km/h/s
   (iv) A period with continuous SM is identified as one SM event.
8) SS (Frequently Stop and Start). A vehicle idles within 3 seconds after starting from an idling. A period with continuous SS is identified as one SS event.
9) BM (Braking Moderately). When decelerating, during 5 seconds, one has the following:
   (i) Deceleration ∈ [−25, −15] km/h/s
   (ii) Product of driving mode codes ∈ (31, 49);
   (iii) Minimum acceleration is no less than −5 km/h;
   (iv) A period with continuous BM is identified one BM event.

Scoring is calculated with a linear equation as follows,

$SCORE\alpha = 40 + (1 - (FPH - 6)/(14 - 6)) \times 60, \qquad FPH \in [6, 14]$,

14 is the maximum fuel consumption and 6 is the minimum. Minimum score is 40 occurring when the maximum fuel consumption is achieved.

Then the authors have used multiple linear regression model to develop a driver evaluation model. Principal Component Analysis has been used and first three principle components have been calculated. Taking three principal components as arguments and vehicle fuel consumption as depend variable, multiple linear regression was used to establish driver’s eco-driving behaviour evaluation model.

Lopez et al has used different algorithms to develop scoring namely genetic, fuzzy inference, driving safety index, random forest regression, Bayesian Ridge regression, support vector regression and multi-layer perceptron regressor and found out than genetic algorithm gives the best results.

Castignani et al uses fuzzy logic control for event detection and also uses weather and day/night info to change the weight of acceleration, braking and steering events as shown on the below figures. Scoring function and weights of each event is given in line with the severity effect of each event.

Wang et al, analysed driver aggressiveness. To increase the number of data they used SUMO to randomly create around 22000 driving styles. For classification of the results, they compared random forest (RF), logistic regression (LR), decision tree (DT), Naïve Bayes Model (NB) methodologies. RF gave the best results. Proportion of bad drivers in N number of drivers was used as a methodology of scoring. This methodology can be applied for insurance policies but for driving style scoring to optimise emissions a numeric relational system is to be used.

Fugiglando et al used eight signals from the CAN bus, namely:

- Brake pedal pressure (BRK)
- Gas pedal position (GAS)
- Revolutions per minute (R.P.M.)
- Speed (SPD)
- Steering wheel angle (S.W.A.)
- Steering wheel momentum (S.W.M.)
- Frontal acceleration (F. ACC.)
- Lateral acceleration (L. ACC.)

They then used K-means clustering algorithm to group the data they collected. This work has concentrated more on driver profile but not on scoring.

3.2. Proposed methodology for Optimum Emission Driving (OED) Style Scoring

The literature survey analysis shows basically two different approaches for scoring. First approach is to carry out event detection and also scoring in a combined manner by using AI methodologies such as random forest and the second methodology is to perform event detection first and calculate the scoring as a second step through a methodology like "Principal Component Analysis". Principal component analysis is usually used when a large number of parameters are involved. In our case only two parameters will be used with deceleration values maximum number of parameters will be four. Therefore, scoring could be merged with event detection process.

In Section 2.1.3 it was decided to use $v.a\_{95\ perct}$. and RPA to determine the driving dynamic events and also deceleration and deceleration frequency for brake and tyre emissions. v.a and RPA can be calculated also for decelerations with the same weight a positive value considering the severity of tyre and brake emissions on human health. RPA gives info about the frequency of accelerations whereas v.a gives info about the value of the acceleration. Kurtyka et.al show also the correlation of v.a and RPA with emissions as has been done by Satlawa et.al.

Reference analysis summary at section 2.1.3 shows that aggressive driving style so high acceleration and deceleration values effect brake and tyre emissions considerably. Therefore, if in RPA and v.a calculations also negative accelerations are taken into account, a trend for brake and tyre emissions will also be determined. In general, aggressive driving tends to worsen all the emissions including brake/tyre emissions. However, frequent deceleration is also not a good way of driving for emissions therefore it should be detected and should be also used in scoring with a relevant weight

The following stages can be used 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

3.2.1. Assumptions

Relation with v.a and RPA and the value of different emission gases and particles are to be determined to check the soundness of the process described above. For example, harsh deceleration is positive on tailpipe emissions but creates a considerable brake and tyre emissions. Another example of adverse trend of emissions is for speeds below 40 km/hr(urban). THC at urban speeds does not seem to be affected by driving dynamics whereas CO_2 and NO_X are affected considerably. However above speeds of 40km/hr driving dynamics influences all the emission values. v.a will be an indicator giving a higher score for the same driving dynamics however at higher speeds.

NO_X at high accelerations does not seem to increase with velocity after around 70 km/hr. However, considering that the other emissions continue to increase still a positive trend can be assumed.

Brake and tyre emissions are also very harmful for human health. Therefore, harsh and frequent decelerations will also be evaluated with the same scoring trend as positive accelerations.

2.1.5- A Case Study to Demonstrate the Methodology.

The following steps have been followed using optiTruck simulator for a heavy-duty truck (HDT).

a) A driving profile on the map has been defined
b) By using the trained parameters obtained from Kurtyka and Satlaw and also from the simulation systema.] random forest algorithm has been used to detect v.a and RPA values above determined thresholds
c) Score is calculated continuously as driving parameters are detected
d) An example on NO_X emissions and the relation with scoring has been shown

In Task 5.3, this case will be extended for many driving styles and different types of vehicles on the simulation system and MODALES training will be developed. The score and different emission values will be checked both for simulation and application.

3.3. Implementation and use of the OED style scoring

As described above, an AI algorithm like random forest can be used to calculate a user's driving score in real time, thus indicating the effect of a given driving style on emissions and generate recommendations accordingly. This algorithm would need to be trained through road tests, which will be performed in WP3, by using the verified simulation system results, and potentially on WP6 during the early trial phases where a first data collection campaign will be done. The critical factor will be implementing the algorithms in such a way that they can work fast enough on modern phones, and consequently, compute scores in (near) real-time to guide the driver.

It is worth noting that at the time of writing this deliverable, the models presented in this document are at a theoretical stage. As far as the mobile app to be developed in MODALES is concerned, the methodology presented above might be adapted depending on the development work constraints and the first datasets to be collected in WP5/WP6.

4. Guidelines and recommendations for low-emission driving behaviour

The information included in this chapter collects the summary of all knowledge on factors that affect emissions individually from tile-pipe, brakes and tyres. As some tests carried out in WP3 were not ready at the time of writing this document, some knowledge has been based on models and existing literature while others also count on recent tests. Thus, the details among emissions from tail-pipe, brakes and tyres are slightly unbalanced.

4.1. Powertrain emissions

As explained in section 2.1.3, regulation (EU) 2017/1151 describes in appendix 7a the methodology to determine the driving dynamics. There v.a and RPA were the main parameters, so it was decided to use these parameters to determine the driving dynamics. In Deliverable 2.1 in section key factors for low emission driving were investigated under following headings,

- Driving speed
- Acceleration/deceleration
- Route
- Idling
- Grade/terrain
- Secondary factors such as air condition, engine temperature, etc.

Analysing the results of the literature survey of D2.1 and also some more recent literature published after D2.1, using also the results of the optiTruck simulation system as shown in section 2.1.2 of this deliverable, guidelines for low-emission driving has been outlined below,

1- When the engine is cold, accelerations and high speed to be avoided;
2- Large accelerations are to be avoided, frequent but small accelerations is better;
3- Especially in urban environment, frequent accelerations are to be avoided;
4- At high speeds high acceleration values cause an asymptotic increase in emissions except NO_X;
5- High speeds are to be avoided;
6- When travelling downhill, engine brake is to be used to prevent acceleration and high speeds;
7- Lower engine torque and lower load will cause lower emissions. In windy weathers speed is to be reduced to eliminate an additional emission due to additional torque requirement. A gradual increase of torque before entering the slopes will help emissions preventing sudden torque requirement;
8- Air condition system is to be avoided as much as possible, if used sudden accelerations are to be avoided.

4.2. Brake emissions

Brake emissions are considered to be one of the major contributors, together with tyre and road wear, to non-exhaust emissions from the road traffic. The relative contribution of non-exhaust sources on the overall $PM_{2.5}$ air pollution coming from the road traffic is reported to be at around

13% [13]. Within this 13% roughly the 50% can be attributed to the emissions coming from the wear of tyres and roads while the other 50% is due to brake wear [22].

4.2.1. Environmental factors influencing the brake emission factors

Wakeling et al. [23] did an extensive study of the contribution of brake wear emissions to the overall particulate matter in ambient air, highlighting the particularly wide variability of their contribution, i.e. they found that the contribution of the brake wear varied from 1.7 % to 11% PM_{10} according to the type of roads considered. Figure 5 shows the trend of the contribution of the brake emissions ($PM_{2.5}$) in UK as a function of the road and vehicle types. Please note that the forecasts in this figure are an estimation based on the strong assumption that no strategies to limit the non-exhaust emissions will be implemented during the temporal range indicated.

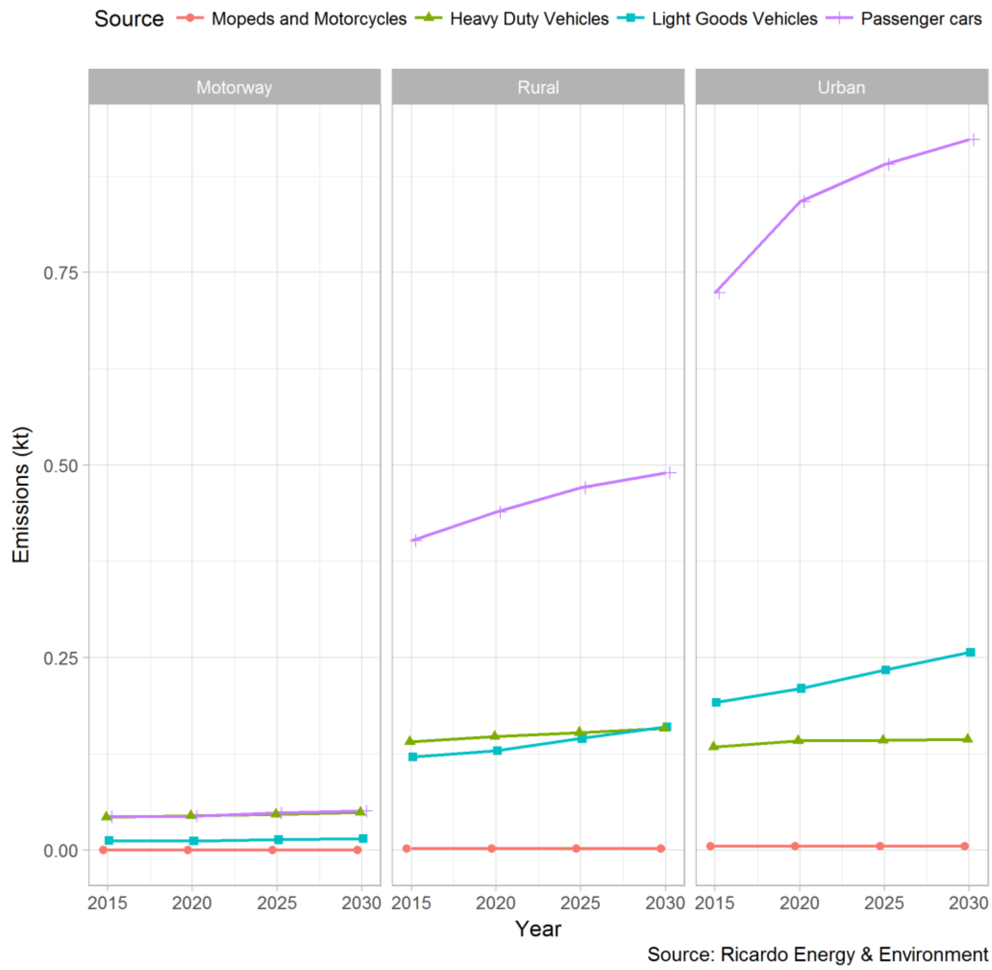

Figure 5: $PM_{2.5}$ from brake wear in the UK for the different vehicle and road types [13]

As can be noted from Figure 5, the contribution of break wear on $PM_{2.5}$ emissions is higher in urban areas. This trend is due to the elevated number of brake actuations. Although the higher velocities and decelerations in rural and motorway areas, the relative contribution of the brake wear emissions on these areas are lower because of the limited number of brake actuations. A further interesting observation is that the contribution of the passenger cars is the highest in all road types. The explanation for this high contribution on the total brake emissions has been found in the large market share of passenger cars. Despite the fact that typical emission factors of these kinds of vehicles are lower than for heavier vehicles, e.g. light duty and heavy-duty vehicles, they account for 84% of the total distance driven in Germany and 78% of distance driven in the UK [14]. These estimations are of key interest to target the most polluting vehicles and to reduce their brake emissions.

Wakeling et al [23] highlighted that there is not a clear correlation between the brake emissions and the hour of the day while they identified a variation from 7.2 mg km^{-1} to 6.1 mg km^{-1} respectively for weekdays and weekend. This variation might be ascribed at the higher road congestion found during weekdays with respect the weekend.

Another parameter evaluated by Wakeling et al was the slope of the roads; they found the correlation with the brake emission factors reported in Figure 6.

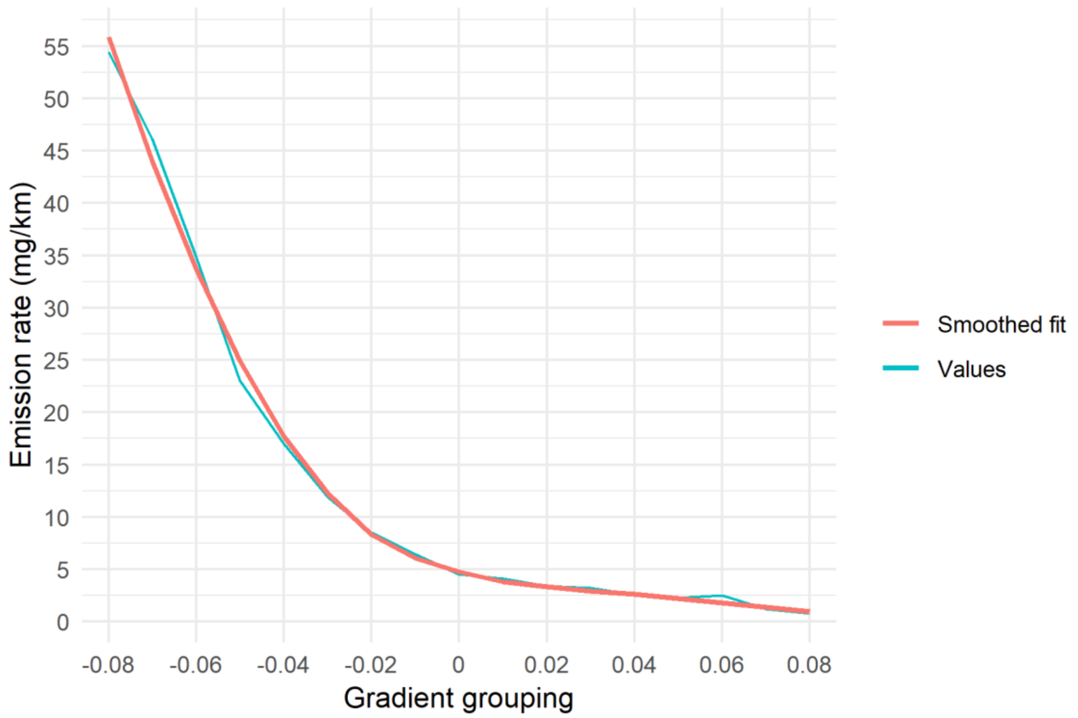

Figure 6: Average brake emission factor as a function of the slope of the road [23].

The data in Figure 6 shows that for a slope equal to – 8% the brake emission factor is higher than 55 mg km-1 while for a road slope equal to +8% the emission factor is lower than 1 mg km^{-1}.

4.2.2. Guidelines

Several studies [22], [23], [24]and [25] have highlighted the crucial role of the energy dissipated by braking on the temperature increase of the braking components. This dissipated energy is the kinetic energy of the vehicle (equation Eq.1 below).

$$E_{kin} = \frac{1}{2}\, m\, V^2 \tag{1}$$

Where m is the vehicle mass and V is the vehicle speed. As can be noted from Eq.1, this energy is proportional with the square of the vehicle speed. Due to this parabolic relationship, even a small decrease in the vehicle speed will reduce significantly the kinetic energy to be dissipated by brakes preventing huge temperature rises. These rises in temperature are strictly related to the increase in the brake wear. Figure 7 shows the specific wear coefficients of three different friction materials as a function of the disc temperature, for simplified lab-scale pin-on-disc tests [25]. The results depicted highlight that above a threshold temperature dependent from the friction material formulations, the wear increases of one order of magnitude.

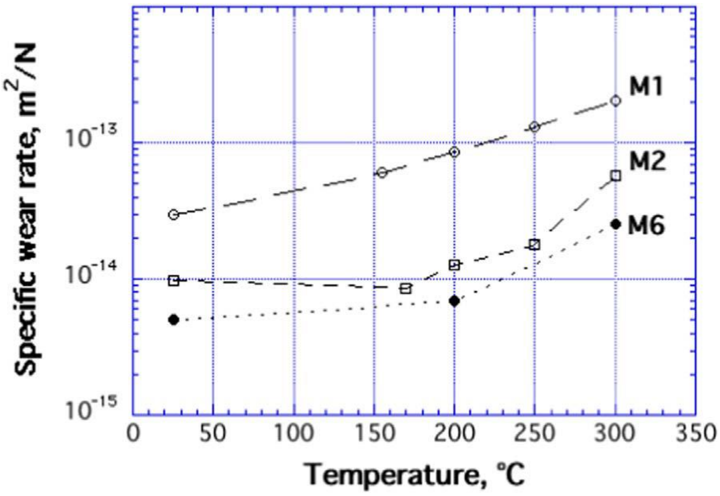

Figure 7: Specific wear rate of three friction materials as a function of the disc temperature [25].

Wakeling et al [23] confirmed the observation of Perricone et al [25] reported in Figure 7 by correlating the airborne emissions with brake temperature, shown in Figure 8 below.

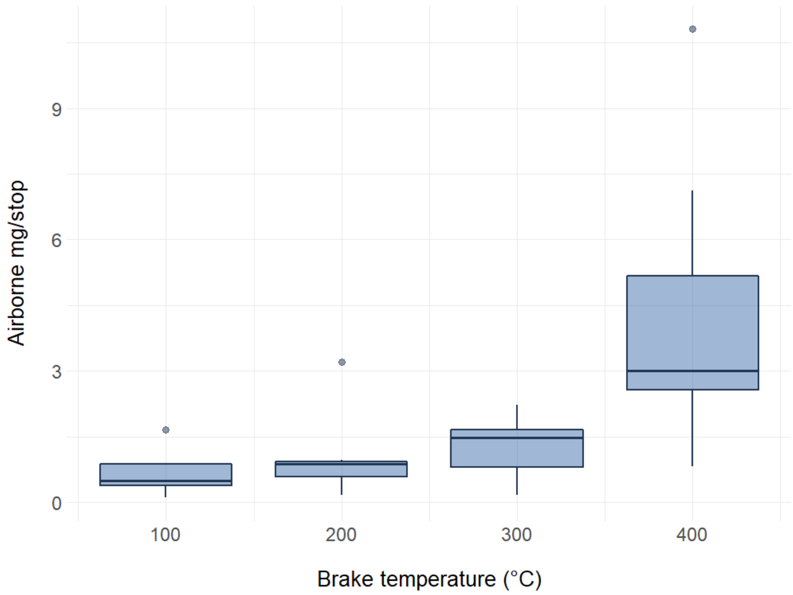

Figure 8: Airborne PM emissions as a function of the brake disc temperature [23].

The main indication to lower the emissions due to the wear of the braking components is to reduce the kinetic energy (Eq. 1) dissipated by brakes in order to avoid significant brake temperature rises during driving.

In order to do that a conservative driving style needs to be adopted and any aggressive behaviour should be avoided. In particular, drivers have to apply a "smooth" driving style, avoiding harsh decelerations, accelerations and limiting the average speed. In general, the same strategies applied for the low exhaust-emission driving can be applied to the brake emissions, nonetheless a deeper insight of the strategies to achieve low brake-emission driving is reported in the following lines.

Several actions might be applied to reduce the kinetic energy of the vehicles without braking, for example, the use of the engine brake torque contributes to slow down the vehicles without acting on brakes. It leads to a lower number of brake applications that have been found as one of the main parameters influencing brake emissions. Moreover, the use of the engine brake torque results in lower and smoother deceleration while driving. Again, a proper use of the engine brake torque is useful to lower the average initial brake speed; by smoothing the velocity profile, avoiding sharp increases and decreases in the vehicle speed, a lower kinetic energy is expected to be dissipated by brakes.

The use of the engine brake torque becomes fundamental to avoid the overheating of the brakes during downhill driving (negative road slope). As depicted in Figure 6, the variation in the brake emissions due to the downhill driving with a limited use of the engine brake torque could be ten times higher than the emissions generated driving on a flat road.

As mentioned above and consistent with the recommendations for reducing the exhaust emissions, to achieve a significant reduction in brake emissions, a conservative driving style have to be applied by modifying the wrong braking behaviour of drivers. The possible guidelines to improve the driver braking experience are listed below:

- 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 high acceleration, that are often followed by strong decelerations. A conservative driving style without abrupt transition in the vehicle speed will lead to lower emissions.

In order to determine the variability of the brake emissions with the driver braking behaviour, some dyno-bench tests have been performed in the Task 3.2. These tests have been carried out with the brake system of a C-segment European passenger car. This car is also the reference one used within the Particle Measurement Programme (PMP) informal working group. The novel WLTP-Brake cycle has been considered as representative of the average driver braking behaviour. A modified cycle has been used to evaluate the variation in the brake emissions with a more conservative driving and braking behaviour. The modification of the brake cycle has been done in accordance to the guidelines described above and so:

- lower decelerations have been used for the most demanding stops;
- lower initial brake velocities have been applied for the most demanding stops.

All the modifications are aimed at reproducing a higher attention of drivers to traffic situations, while the nominal mileage of the WLTP-Brake cycle remained unchanged as well as the cycle division into ten trips. Further information about the WLTP-Brake cycle is collected in [26].

The modified version of the WLTP-Brake cycle, named mild WLTP-Brake, showed a decrease in the total energy dissipated by brakes of the 20% with respect the reference WLTP-Brake cycle. As discussed at the beginning of this section, the decrease in the kinetic energy dissipated by brakes leads to the decrease in the brake disc temperature. In order to evaluate the disc temperature reduction, the six most demanding stops of the WLTP-Brake cycle have been evaluated in terms of variation in kinetic energy dissipated, initial brake temperature (IBT) and final brake temperature

(FBT). These stops are actuated during the tenth trip of the testing cycle. The results are reported in Table 4. These are the percentage reductions in the temperature parameters detected with the mild version of the testing cycle with respect to the reference one.

Table 4: Percentage decrease in the brake disc temperature.

Brake ID (Trip 10)	Decrease in the Kinetic Energy (%)	Decrease in the Initial Brake Temperature (%)	Decrease in the Final Brake Temperature (%)
46	58	23	25
101	23	48	20
102	35	30	28
103	30	31	42
104	41	30	29
106	31	42	29

Moreover, the average disc temperature during the trip ten decreased by 29%.

Table 5 collects the PN_{10} decrease detected during the same braking actions Table 4.

Table 5: Decrease in PN10 emissions during the most demanding stops of the Trip 10.

Brake ID (Trip 10)	Decrease in PN_{10} (%)
46	45
101	50
102	77
103	94
104	77
106	64

The overall reduction, along the entire testing cycle, in PN_{10} was equal to the 52%, confirming the promising results showed in Table 5. Moreover, also the PM_{10} emission factor has been reduced of the 48% by applying the guidelines above. These results are particularly promising and show that from a limited decrease in the kinetic energy, equal to 20%, leads to a significant decrease, approximately of the 50%, in the brake emissions.

4.3. Tyre - Road emissions

Knowledge on tyre and road emissions can be found in MODALES Deliverable 2.1, Chapter 5. Tests conducted on tyre and road emissions in Task 3.3 also consolidate the literature review. Combining this knowledge, it was seen that tyre and road emissions are very much dependent on the driving style. High velocity, sudden acceleration and deceleration, lateral and vertical acceleration deceleration (i.e. sharp cornering and going over bumps fast) will also influence the emission considerably.

Besides driving style as in the case of other types of emissions, the weight of the vehicle is also an important parameter. Overload and carrying of unnecessary weight is to be avoided. Therefore pre-trip considerations are also important. Appropriate use of winter/summer tyres, right tyre pressure, proper maintenance of tyres, road type selection (less hilly and less coarse roads) will all contribute positively to the tyre/road emissions as pre-trip preparation.

The guidelines resulting from this knowledge can be seen in Chapter 6 of the present document.

4.4. Tampering and lack of maintenance

There is considerable evidence that many vehicles operating on the roads would not achieve the appropriate emission standards. It has been found that vehicles that are poorly maintained or malfunctioning are important contributors to air pollution [27]. When the engine settings are not in accordance with manufacturers' specifications, it is not surprising that their performance deteriorates [28]. To overcome this situation, countries have developed Inspection/Maintenance (I/M) programmes. A major element of many programmes to control exhaust emissions from vehicles in use is a requirement for them to be examined periodically and, if their emission rates do not conform to the standards, for them to be adjusted or repaired.

The goal of an I/M programme is to ensure that vehicles remain safe, in good working order throughout their lifetime, and do not produce excess pollution. At the core of an I/M programme is the requirement that vehicle owners regularly submit their vehicles for a standardised inspection. If the vehicle fails inspection, it needs to be repaired and re-inspected before it returns to normal operation [27]. The most common way of examining the influence of vehicle maintenance on rates of emission and fuel consumption has been to test vehicles taken from normal service. Then it is possible to compare their performance with the standards to which they were built and/or to retest them after servicing the vehicles to comply with the manufacturers' recommended engine settings, thus determining emissions in the “correct” condition for comparison with the original values [29].

In theory, I/M will result in greater emission reductions from new vehicle standards because the emission control systems continue to operate at high control efficiency through the vehicle’s useful life. I/M also improves emissions from the current fleet of older vehicles with less advanced control technology during the transition to more stringent standards [30] and [31].

Several studies carried out have shown that diesel engines usually deteriorate to have higher PM, CO and HC emissions and lower NO_x emissions. The effect of engine faults and maintenance procedures on emissions usually follows the NO_x/PM trade-off. Engine faults that increase PM usually reduce NO_x emissions and vice versa. This also means that repairs to correct high PM emissions will increase NO_x emissions. Restoring engine settings and performance to factory settings is the only way to balance the two and to ensure that PM or NO_x emissions do not become excessive. The most common diesel engine faults and a qualitative estimate of their frequency of occurrence are listed in Table *6*, which presents the work done in 2001 (McCormick 2001 [32]) as well as additional information to reflect advances in diesel engine technology since that time.

Some of the useful tips on car maintenance include:

- 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.

Table 6: Effect and Frequency of Faults in Heavy-Duty Diesel Engines [6]

Components	Effect on Emissions	Frequency
Air filter clogging (dirty)	Increased PM and CO; can increase full throttle PM considerably	Extent of blockage varies, but is relatively common
Turbocharger seals worn	Can leak oil and cause increased PM and hydrocarbons	Minor oil leaks are common in older engines
Turbocharger damage	Significant damage is catastrophic, but minor damage has little effect on emissions	Minor leaks on turbo are common
Intercooler internal leaks	Coolant induction can cause white smoke	Rare
Intercooler - restricted coolant flow	High charge temperature will increase PM and NOx	Unknown
Valve timing	Incorrect valve timing can have a minor emissions effect, although the OBD should alert in case of under-performance	Variable valve timing systems can be susceptible to problems on older cars
Valve leaks	Loss of compression and high PM; engine is hard to start	Relatively rare, self-correcting due to poor start ability
Governor RPM setting	Increased RPM setting can increase hydrocarbons, CO and PM in some trucks	Common among independent trucks (tampering)
Maximum fuel stop setting	Increased hydrocarbons, CO and PM at full throttle	Relatively rare but can occur for certain engine models (tampering)
Injection timing setting	Advance causes increased NOx, retard increased hydrocarbons, CO and PM	Unknown
Air-fuel ratio control	Causes excessive PM during acceleration	Common among independent trucks (tampering)
Worn injector spray holes	Increase hydrocarbons, CO and PM	Occurs in older trucks
Injector plugging	Asymmetric spray can cause increase hydrocarbons, CO and PM	Occurs in older trucks
Injector tip cracking	Excessive PM, but is catastrophic to engine	Unknown
Incorrect injector size	Effect can vary, but hydrocarbons, CO and PM increase with increasing injector size	Could be common in replacement of injectors
Worn piston rings	High PM from low compression/oil leak	Relatively rare, as vehicle is hard to start
Leaking valve seals	Blue smoke from oil consumption, hydrocarbons increased	Unknown
Wrong part numbers	Minor effects if mismatch is not severe	Unknown, but could be a problem with aftermarket parts
EGR valve - low EGR	Increased NOx emissions	Unknown

Components	Effect on Emissions	Frequency
flow		
EGR valve - excessive EGR flow	Increased particulate matter and CO emissions	Unknown
Diesel particulate filter damaged	Increased CO and PM emissions	Unknown
Diesel particulate filter blockage	May have little noticeable effect on emissions	Severe blockage would be self-correcting as the engine may lose power
NO_x after treatment damage or malfunction	Increased NOx emissions	Unknown

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

Tampering has a direct effect on the regulated emissions and can also affect the unregulated emissions. Tampering has been observed in a large proportion of engines with mechanical fuel injection systems that were tested under I/M smoke tests. Tampering, in the form of modified engine management software, is believed to be common in newer electronically controlled engines [33]. Tampering can occur with on-road light-duty vehicles (i.e., cars and light trucks), heavy-duty trucks, and off-road vehicles and engines (e.g., recreational vehicles or off-road equipment).

As the sophistication of emission controls required to conform to emission standards has increased, the types of tampering have become increasingly complex. Tampering with vehicle or engine emission controls includes [34]:

- removing, bypassing, defeating or rendering inoperative any emission control system or device installed in or on a vehicle or engine, including software designed to monitor or control vehicle or engine emissions.
- modifying the vehicle or engine in any way that results in increased emissions from the level to which it was originally designed/certified by the manufacturer or importer of the vehicle or engine.

Tampering with, or illegally modifying, emission control devices can substantially distort a fleet's impact as only a few high emitting vehicles with improperly working/removed emission control devices can be held responsible for disproportionally high contributions to poor local air quality [35]. According to the United States Environmental Protection Agency [36], when a tuner enables the full removal of emissions controls ("Full delete emission controls"), there is an increase in NO_x, NMHC, CO and PM. Some tests that were conducted without the SCR (selective catalytic reduction), DPF (diesel particulate filter), DOC (diesel oxidation catalyst) and EGR (exhaust gas recirculation) emission controls have shown that NO_x increased by ~310x, NMHC increased by ~1.140x, CO increased by ~120x and PM increased by ~40x as shown in Figure 9.

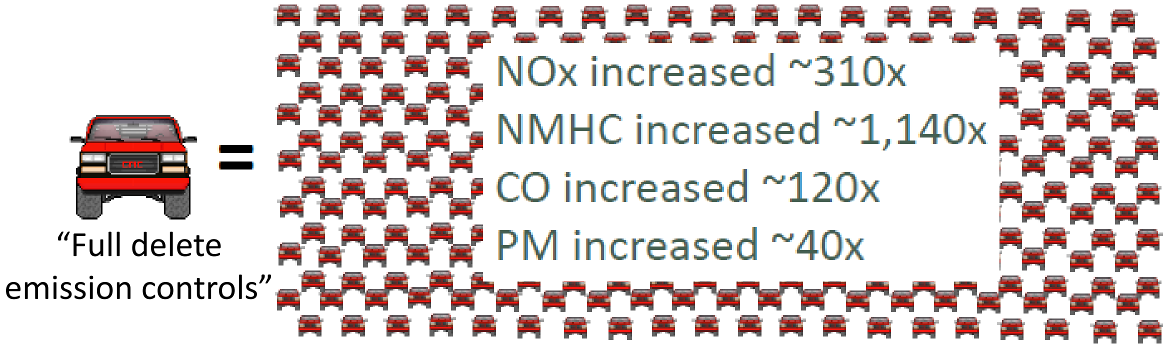

Figure 9: Comparison between a “full delete emission controls” vehicle with full emission controls equipped vehicles [10]

Some defeat devices and tampering examples, according to Frank Acevedo and Cody Yarbrought [37], are listed below [38]:

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

Tampering has been observed in a large proportion of engines with mechanical fuel injection systems that were tested under I/M smoke tests. Tampering, in the form of modified engine management software, is believed to be common in newer electronically controlled engines [32]. Tampering can occur with on-road light-duty vehicles (i.e., cars and light trucks), heavy-duty trucks, and off-road vehicles and engines (e.g., recreational vehicles or off-road equipment). Over-fuelling to increase engine power by advancing the maximum fuel stop on engines with mechanical fuel injection systems is relatively easy for certain engine models and relatively common for those models. Advanced injection timing due to tampering may occur when retarded injection timing was often used to meet NO_x standards [33].

Removing DPF: Due to the high replacement costs, complete removal of the filter becomes an attractive solution if it can go unnoticed by enforcement measures, for instance during periodic technical inspection (PTI). By removing the DPF, the ECU needs to be “re-flashed” to delete the pressure sensor from the on-board diagnostics (OBD) ‘scanning field’ or to simulate its functionality.

Disabling the EGR can easily be done by means of deleting its functionality from the engine control unit (ECU) via a remapping (reflash). Another option is to mechanically block the EGR gas tube or by sealing the hose to the vacuum actuator, although this form of tampering is more susceptible to being noticed during a periodic technical inspection (PTI).

SCR removal: SCR systems require an AdBlue injection to allow for a NO_x reduction. Typically, AdBlue consumption is equivalent to 3-5% of the fuel consumption of a vehicle and the cost of AdBlue is approximately half that of diesel [38]. Therefore, the incentive for truck owners/fleet operators to disable the SCR becomes viable. 'Removals' take place in two ways:

- Physically using an emulator that is placed between the SCR's sensor(s) and the engine's ECU to limit its functionality
- Software-wise by re-flashing the ECU.

In general: SCR tampering is mainly an issue for the heavy-duty market (for now), while DPF and EGR tampering, as well as chip-tuning typically occurs on passenger cars.

The focus concerning pollutant emissions is generally set on diesel cars. However, one should not forget that petrol cars can be manipulated as well, although such measures are far less common in daily practice. A German study on the performance of aftermarket (non-OEM) three-way catalysts revealed that many of them are nearly uncoated and thus ineffective in converting pollutants. As a result, repaired petrol cars may emit NO_x emissions many times higher than allowed. A TÜV Nord investigation, in fact, pointed out that 3 out of 4 EU Certified aftermarket catalysts did not work correctly. Moreover, 3.5 million of these devices are estimated to be installed in Germany alone, with about 1% of them currently detected during PTI [39]. This indicates both the need for a robust testing of aftermarket devices and an adequate methodology to detect high emitters.

Today, many researches have been performed on this area providing variable patents and methods against tampering. Geilen et al. (2014) [40], developed a vehicle testing system which is directed to vehicle testing, and in particular to a method and apparatus for detecting whether an on-board diagnosis system of a vehicle has been improperly tampered with or altered. The present invention provides a method and system for detecting whether a vehicle has been improperly tampered with to prevent detecting that the vehicle does not comply with vehicle regulations by detecting improper modification of a vehicle via the vehicles on-board diagnosis system.

As it is observed, the issue of vehicle tampering is of outmost importance and only through strong legislation, issued through European Regulations, and the implementation of effective enforcement against tampering, will consumers and companies no longer be tempted to illegally modify their vehicles.

As general guidance, some examples of acceptable practices to minimise the risk of tampering with in-use vehicles or engines include [34]:

1. Qualified technicians should only maintenance and repair the emission control systems or the devices related to emissions. This does not preclude service or maintenance work performed at an independent repair shop. Vehicle warranties usually cover emission control systems and devices for a specified period; however, if the emission control system or device is tampered with during the warranty period, a manufacturer may not honour the warranty.

2. An emission control system or device may be removed at any time if it is being replaced with one that is (a) designed for that vehicle and (b) at least equally effective in reducing emissions. As an example, a damaged or failed catalytic converter can be replaced with either an original equipment manufacturer's replacement for that vehicle or an aftermarket catalytic converter that meets the emission standards for that vehicle.

3. When replacing the engine in a vehicle, the replacement engine should meet or exceed emission standards of the same vehicle classification and model year as the vehicle chassis and all the associated emission control systems and devices should be connected. Engine

replacement should not result in an older or different configuration designed to a less stringent emission standard.

4. Only fuel that is appropriate for the engine design should be used. The installation of alternative fuel conversion equipment is not considered tampering if the converted vehicle or engine will continue to function properly and its emissions will not increase as a result of the conversion.

5. An older vehicle or engine may be retrofitted with verified emission control equipment or be otherwise modified to decrease emissions from the level to which it was originally designed/certified. This would not be considered tampering.

5. Implementation and exploitation of the guidelines

The guidelines developed in Task 5.1 and proposed in this deliverable will be used in several forms. The goal of the project is to disseminate the guidelines to the final users (transport operators and drivers) through multiple channels. One of the forms of dissemination, linked to the pilot-sites will be the training of the participating drivers on how to emit lower emissions while driving. The guidelines will be the foundation for the development of the training and can be used in several approaches in order to give emphasis to the most impactful aspects of emitting and how this could result to savings. Several versions of the guidelines will be published throughout the project-life targeting different audiences. Additionally, the guidelines can be used as input for future developments, as applications, driving simulators etc.

Hereunder, the main exploitation categories are presented:

- Training course: The Guidelines will be the main input utilised in Task 5.5 by elaborating actions and behaviours that could create a positive and measurable environmental impact.
- MODALES app and similar technological solutions: Basis for games, driving simulators or similar apps.
- Speaking opportunities at events: During the project-life, there will be speaking opportunities related to industry-relevant events, internal events in associations, e.g. IRU Committees, and similar events where MODALES partners will be able to promote the project's results, look for feedback etc.
- Dissemination to key stakeholder: National associations, key corporates, driving schools
- Social media: 2-3 minutes video with the top guidelines
- Articles – publications: MODALES partners are going to disseminate the project results (progress, final results etc.) by publishing articles at industry websites and magazines and also by using channels such as: websites of the participating stakeholders (IRU, FIA, ERTICO etc.), newsletters (ACASA, IRU...), publications on scientific journals and/ or conferences.

5.1. Training

The training of the drivers (both professional and private) will be delivered in the framework of MODALES project in order to communicate the best practices to the targeted user groups. The development of the training material is part of the MODALES task "Training for low-emission driving" (T5.5) and will consist of the output of WP2 and WP3. Output from the present deliverable will be transferred into tangible, measurable actions - guidelines providing valuable input for the training and the whole dissemination strategy.

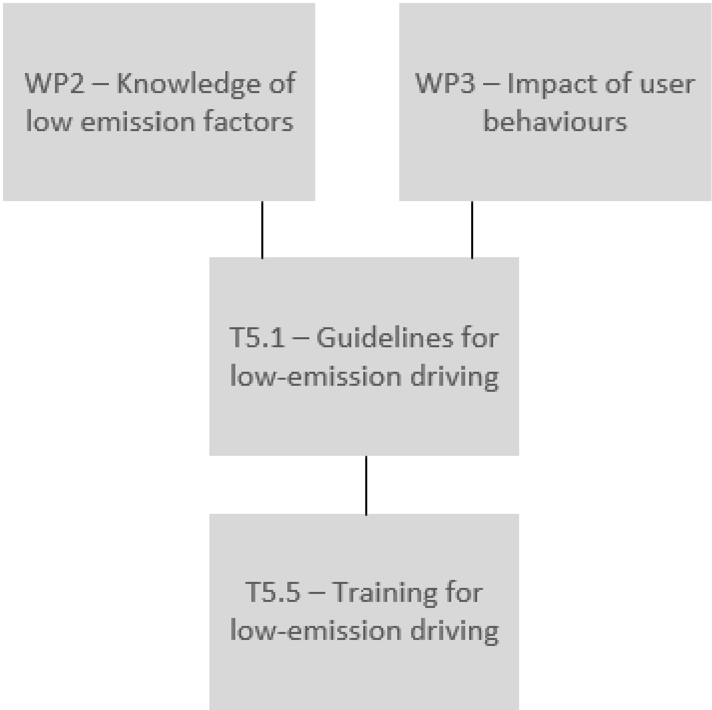

Figure 10: Tasks feeding "Training for low-emission driving

During the planning phase of the project, live training sessions were planned to take place at pilot-site level. Additionally, train-the-trainer approaches and useful documentation (manuals etc.) would support trainers and drivers to enrich the learning process maximizing the impact However, the global pandemic due to the COVID-19 challenged the traditional training methods, making travelling risky and sometimes not even possible due to the local restrictions for travellers. The MODALES partners had to adjust on the situation and deliver results finding alternative possibilities to deliver trainings through online events, videos by the trainers - experts or the creation of a MOOC-style course. However, there are barriers to be considered as the language, the active participation and the way the trainees will be able to ask questions in order to fully understand and make use of the techniques presented. The MODALES consortium is going to explore the different approaches and come up with the most suitable one or a combination of multiple approaches.

The training modules are going to include all the different knowledge produced in the project together with already existing best practices. The three main aspects covered are as presented in Figure 11).

Figure 11: Training - aspects covered

Regarding proper maintenance, this will take into consideration different vehicle types.

The targeted user groups will be focused on the following three categories, as presented in Figure 12.

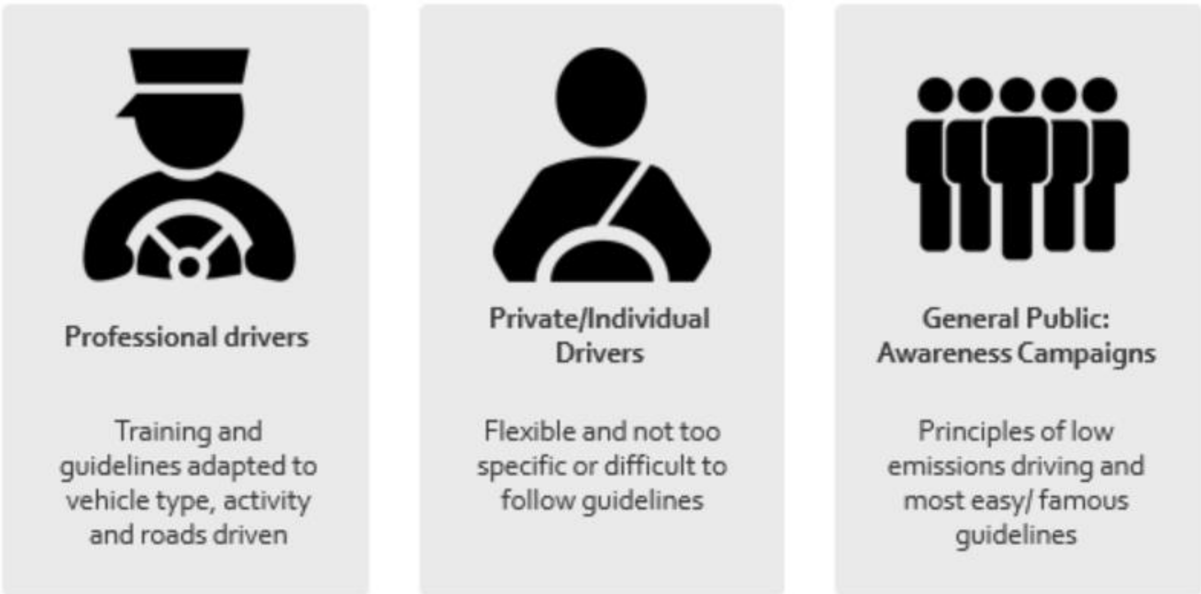

Figure 12: Targeted user groups

5.2. Input for the application

The guidelines presented in this document will serve as a first source for developing the recommendation logic that will be proposed by the DALED mobile app, which is also to be developed in WP5. The methodology to develop this mobile app and the technical specifications are described in D5.2, which is a complementary deliverable to D5.1, explaining in particular how to convert the guidelines described in this document into a software solution usable by an end-user.

The recommendations generated by the mobile app will be in two different formats:

- **Active recommendations** will be given to the user while driving. This recommendation format will be simplified and will mainly consider a driving score calculated in real-time on the mobile phone. These recommendations should be simple and should not compromise the safety of the driver, for example by displaying colour codes on the whole screen. The method for calculating the score will be based, if possible, on the method described in the present deliverable, but other options will also be explored based on the constraints measured in the first experiments (T6.2).
- **Passive recommendations** will be given as a detailed report to the driver after each trip. These recommendations will, by nature, be much more complex and will consider more data, all detailed below.

These two recommendation formats will be generated based on the conclusions of the present deliverable, and in a readable format, as given in the table below, which summarises the impact factors of various metrics on the three emission sources. These factors are decomposed into three categories, and will, as far as possible, have to be estimated by the mobile app to generate recommendations:

- **Environmental factors** describe what is independent of the user, e.g. the presence of a traffic jam or the weather.
- **Vehicle-dependent factors** focus on the vehicle model used by the user.
- **User-dependent factors** focus on the user's driving style and profile, each of which has a direct influence on emissions.

The mobile app will consider this matrix, in addition to additional information from WP3, which at the time of writing D5.1 is not yet finalised. A possible approach will be to implement a rule-based system, in which the recommendations will be selected according to the individual value (measured or estimated) of each metric, with different levels of priority to be defined. Other approaches are possible and are detailed in D5.2, such as the use of classification mechanisms to compare driving profiles between users and give them similar levels of recommendations. Finally, it should be noted that all the metrics in this table are detailed in D5.2, where a calculation and estimation method is provided.

It should also be noted that WP5 will develop, in addition to the mobile app, a web dashboard which will aggregate anonymous indicators produced by the mobile app and intended for public bodies and local authorities. This dashboard will consider, to the greatest possible extent and when deemed relevant, the guidelines described in this document.

5.3. Awareness and dissemination campaigns

The awareness and dissemination campaigns are going to mainly target the general public. The communication main channels utilised will include social media campaigns using Twitter, LinkedIn, newsletters and website posts. The objective of these approaches will be to inform wider audiences such as the general public, OEMs, transport operators, professional drivers and transport companies, research institutes, academia) on the importance of low-emission driving and the easiest / easily applicable actions to reduce pollution.

The MODALES website will serve as an interaction space for the project's relevant information supporting low-emission driving. The website will integrate social medial tools such as Twitter, Facebook and LinkedIn for active participation and support of the wider community that will surround the project. A promotional flyer including the guidelines can be distributed (in print and/or electronic forms) to a broad range of potential stakeholders. The flyer might be followed up with a project brochure describing the MODALES activities and goals in greater detail, always having in mind to promote the guidelines for low-emission driving. Audiences will also be invited to subscribe to the LinkedIn group of MODALES which will post relevant content during the project. Flyers, brochures and newsletters will be made available on the MODALES website.

Workshops may also be organised – both physical and/or virtual – to advance the aims of the project and to involve as many relevant stakeholders as possible. Material may be translated into the local language of the pilot sites in order to attract the attention of local stakeholders and the understanding of locals. Consortium partners will also be encouraged to share relevant material on the guidelines promoting low-emission driving on their communication channels.

Considering the diverse nature of the consortium partners, each will play a role in raising awareness and disseminating MODALES material. ERTICO, FIA, IRU and RACC will focus on consulting their members and associations. Brembo, Bridgestone and Michelin will utilise their networks to disseminate information in the OEM field. Moreover, Cerema, CERTH, Istanbul Okan University, University of Leeds and VTT will ensure that transport academia stakeholders are well informed about the developments of the project.

5.4. Audience and channels to be utilised

As stated in section 1.2.2 scope and intended audience of this deliverable, the proposed guidelines are directed to a wide audience, from driving schools to transport associations and any other entity that wants to promote low emission driving. Thus, these guidelines should be adapted to the channels to be used for communicating the principles of low emission driving, in particular:

- Leaflets
- Roll ups
- Infographics
- On-line course
- Courses in-person
- Workshops
- Webinars
- Conferences
- Driving courses
- User forums
- Apps for Driving Assistance and Navigation.

Three main groups of audiences have been identified:

General Public: Awareness Campaigns

Awareness campaigns are going to be designed to grab the general public's attention on low-emission driving, such as principles of low-emission driving and most easy/famous tips. The material will need to include simple and easily understandable content that any person without expertise on the topic will be able to understand.

Private/Individual Drivers

Private/individual drivers may have different driving behaviours depending on the trip purpose. For instance, driving on weekends on rural roads as opposite to driving on weekdays on congested urban roads. Guidelines should be flexible in order for individual drivers to use them efficiently. Guidelines should also not be too specific or difficult to follow.

Professional Drivers

Professional drivers already have a wide experience on driving so dissemination material directed to them cannot give obvious information. Also, due to their professional activities they may use most frequently the same type of vehicle and drive along the same kind of roads.

- Adapted to type of vehicle (trucks, taxis, buses, light duty vehicles etc.)
- Adapted to their activity (last mile delivery, freight road transport passenger transportation, private use)
- Adapted to the type of road they usually drive (hilly areas, motorways, rural....)
- Adapted to congestion level of the route
- Adapted to the level of experience of the professional driver
- Adapted to the type of cargo transport/number of passengers carried.

Table 7: Approaches on exploitation and dissemination of the guidelines

Targeted audiences	Approach	Channels
Private companies interested on low-emission driving, professional drivers (freight, taxis, public utilities, etc.) and their associations, private drivers, driving schools etc.	Training	MODALES pilot-participants, online video course, in person training, webinars, training schools
Users of applications for low-emission driving, trainees on low-emission driving simulations.	Input for technology solutions	Application developers, simulation developers, video games developers, Apps for driving assistance and navigation
National transport associations, shippers, key corporates, driving schools	Dissemination to key stakeholder	Utilisation of the partners' network, social media, newsletters, websites
Researchers, industry and other experts involved in driving behaviour and emissions reduction	Presentations at events, articles and publications	Congresses/Conferences, technical and scientific publications, presentations, press articles, position papers.
General public, private drivers, future drivers	Dissemination to the general public	Social media, newsletters

6. Conclusions and next steps

In order to identify the guidelines, the first step was to determine the effect of different driving styles under different environmental and road conditions on emissions. This analysis was carried out in MODALES WP2, which focused on the definition of different driving styles and their effect on tailpipe, brake and tyre emissions.

The main factor influencing emissions of all type 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.

An additional literature survey has been carried out within Task 5.1 and detailed at section 4 of this deliverable. The main WP2 findings (especially for tyre emissions) were merged with Task 5.1 literature review to summarise guidelines according to three main factors (Environmental, Vehicle-dependent and User –dependent) and for the following areas of action:

- Powertrain emissions
- Tyres emissions
- Brakes emissions
- Lack of maintenance and tampering.

Guidelines related to maintenance and tampering have been associated to the powertrain, tyres, or brakes areas according to the relevance summarised at

Table 9. It is therefore possible to arrange the main guidelines extracted from WP2 and Task 5.1 literature review into a single table (Table 8) according to the factor, and areas of actions.

Table 8: Summary of MODALES guidelines for driving

Factor	Powertrain emissions	Tyres emissions	Brakes emissions
Environmental	• Select Route with low slope and/or higher straight line • Select Route with Lower Traffic (at comparable distance) • In windy weathers speed is to be reduced to eliminate an additional emission due to additional torque requirement. A gradual increase of torque before entering the slopes will help emissions preventing sudden torque requirement.	• Select Route with low slope and/or higher straight line • Select Route with Lower Traffic (at comparable distance) • Use Correct Season Tyres (Summer - Winter - A/S) • In case of available road characteristic info select road with low micro-roughness	• Select Route with less urban areas and more highways • Select Route with Lower Traffic (at comparable distance)
Vehicle-dependent	• Lower engine torque and lower load will cause lower emissions. • 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.	• 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 (when available)	

Factor	Powertrain emissions	Tyres emissions	Brakes emissions
	• Keeping the air filter clean will also protect the environment	• For Electrical Vehicles optimise Equilibrium between Battery Regeneration and Tyre Wear • 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.	
User - dependent	• Accelerations and high speeds are to be avoided (especially when the engine is cold) • High accelerations are to be avoided, frequent but small accelerations is better • Especially in urban environment, frequent accelerations are to be avoided. • At high speeds high acceleration values cause an asymptotic increase in emissions except NOx • When travelling downhill, engine brake is to be used to prevent acceleration and high speeds • Air condition system is to be avoided as much as possible, if used sudden accelerations are to be avoided	• Avoid high acceleration/deceleration both Transversal ,Longitudinal and vertical • Reduce car (use alternative mobility solutions) usage in case of short Time (Thermal state of Tyre) • Use moderate speeds • Tyre position rotation	• 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, a higher attention of the driver will reflect a higher use of the engine to slow down the vehicle without using brakes; • avoid high acceleration, that are often followed by strong decelerations. A conservative driving style without abrupt transition in the vehicle speed will lead to lower emissions.

According to Section 5 (Implementation and exploitation of the guidelines), these guidelines will be the foundation for the development of the training and can be used in several approaches in order to give emphasis to the most impactful aspects of emitting and how this could result to savings.

The development of the training material is part of the MODALES task “Training for low-emission driving” (T5.5). These guidelines will be transferred into tangible, measurable actions providing valuable input for the training.

The guidelines will also serve as a first source for developing the recommendation logic that will be proposed by the DALED mobile app, which is also to be developed in WP5 (development methodology and technical specifications in D5.2). The recommendations generated by the mobile app will be in two different formats:

- **Active recommendations** will be given to the user while driving. This recommendation format will be simplified and will mainly consider a driving score calculated in real-time on the mobile phone.
- **Passive recommendations** will be given as a detailed report to the driver after each trip. These recommendations will, by nature, be much more complex and will consider more data.

Precise recommendations, their content, and the way to transmit them to drivers (HMI) will be decided later. Short tips based on previous guidelines can be easily displayed after each trip according to the observed behaviour, while only very simple information can be provided to the driver while driving.

Tips & recommendations will be decomposed according to three categories of emission factors:

- Environmental factors
- Vehicle-dependent factors
- User-dependent factors.

These factors will, as far as possible, have to be estimated by the mobile app to generate recommendations. A possible approach will be to implement a rule-based system, in which the recommendations will be selected according to the individual value (measured or estimated) of some metrics associated to the guidelines, with different levels of priority to be defined.

It should also be noted that WP5 will develop, in addition to the mobile app, a web dashboard which will aggregate anonymous indicators produced by the mobile app and intended for public bodies and local authorities. This dashboard will consider, to the greatest possible extent and when deemed relevant, the guidelines described in this document.

Table 9: Summary of MODALES Guidelines for pre-driving, maintenance and tampering

Guideline	Relevance		
	Powertrain	Brakes	Tyres
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			X
Getting regular tune-ups will go a long way to increasing fuel efficiency and improving the lifespan of the vehicle	X		
Changing the oil regularly will contribute to a cleaner engine and lower vehicle emissions	X		
Keeping the air filter clean will also protect the environment.	x		

References

[1] TREATISE EU-funded project (2007). Retrieved from: https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/treatise_teatrise_report_en
[2] ECOEFFECT EU-funded project (2013). Retrieved from: https://ec.europa.eu/energy/intelligent/projects/en/projects/ecoeffect
[3] CIVITAS eco-driving training for bus drivers (2010). Retrieved from: https://civitas.eu/measure/eco-driving-training-bus-drivers
[4] Kesko Logistics eco-driving (2010). Retrieved from: https://www.resourceefficient.eu/en/good-practice/kesko-logistics-trains-drivers-eco-driving
[5] Strömberg, H.K.; Karlsson, I.M. (2013). Comparative effects of eco-driving initiatives aimed at urban bus drivers–Results from a field trial. Transp. Res. Part D Transp. Environ. 22, 28–33. V
[6] K. Boriboonsomsin, A. Vu, and M. Barth, (2010). Eco-driving: pilot evaluation of driving behavior changes among us drivers, University of California Transportation Center.
[7] Sullman, Mark & Dorn, Lisa & Niemi, Pirita. (2015). Eco-driving training of professional bus drivers – Does it work?. Transportation Research Part C: Emerging Technologies. 58. 749–759.. 10.1016/j.trc.2015.04.010.
[8] Wang, Yang & Boggio Marzet, Alessandra. (2018). Evaluation of Eco-Driving Training for Fuel Efficiency and Emissions Reduction According to Road Type. Sustainability. 10. 3891. 10.3390/su10113891.
[9] Bus eco-driving in Brussels – STIB (2014). Retrieved from: https://www.stib-mivb.be/irj/go/km/docs/resource/tickettokyoto/en/cases/bus-eco-driving-brussels-stib.html
[10] Bus eco-driving in Bielefeld – MOBIEL (2014). Retrieved from: https://www.stib-mivb.be/irj/go/km/docs/resource/tickettokyoto/en/cases/bus-eco-driving-bielefeld-mobiel.html
[11] ECODRIVEN EU-funded project, (2008). Retrieved from: https://ec.europa.eu/energy/intelligent/projects/en/projects/ecodriven
[12] ecoDriver EU-funded project (2017). Retrieved from: https://ctag.com/en/finalizacion-del-proyecto-europeo-ecodriver/ & https://cordis.europa.eu/project/id/288611
[13] "Non-exhaust emissions from road transport Causes, consequences and policy responses", OECD, Environment Directorate, 25th of June, 2020
[14]Barlow, Latham,McCrae, Boulter, "A reference book of driving cycles for use in the measurement of driving cycles", TRL Limited, June 2009
[15] Zhiqiang Zhai , Ran Tu , Junshi Xu, An Wang and Marianne Hatzopoulou, "Capturing the Variability in Instantaneous Vehicle Emissions Based on Field Test Data", Atmosphere 2020, 11, 765; doi:10.3390/atmos11070765
[16] Ying Yao, Xiaohua Zhao , Chang Liu , Jian Rong,Yunlong Zhang,Zhenning Dong and Yuelong Su, "Vehicle Fuel Consumption Prediction Method Based on Driving Behavior Data Collected from Smartphones", Journal of Advanced Transportation,Volume 2020
[17]Timothy Bodisco and Ali Zare, "Practicalities and Driving Dynamics of a Real Driving Emissions (RDE) Euro 6 Regulation Homologation Test", Energies 2019, 12, 2306; doi:10.3390/en12122306
[18]Mateusz Satlawa , Piotr Pajdowski, Dariusz Pietras "The Impact of the Driver's Driving Style on the EXHAUST Emissions of a Passenger Car during a Real Road Cycle", SAE International,Published Sept 15,2020

[19]Karolina Kurtykaa, Jacek Pielechaa, "The evaluation of exhaust emission in RDE tests including dynamic driving conditions", 13th International Scientific Conference on Sustainable, Modern and Safe Transport (TRANSCOM 2019),May 2019

[20] EUROPEAN COMMISSION REGULATION (EU) 2016/646

[21] optiTruck EU-funded project (2019). Retrieved on November 20, 2020 from: www.optitruck.eu

[22] D. Wakeling, T. Murrells, D. Carslaw, J. Norris, L. Jones, (2017). The contribution of Brake Wear Emissions to Particulate Matter in Ambient Air, FAT-SCHRIFTENREIHE 301. Retrieved from: https://www.vda.de/de/services/Publikationen/fat-schriftenreihe-301.html.

[23] D. Wakeling, T. Murrells, D. Carslaw, J. Norris, J. Virdo, (2019). Air Quality Modelling on the Contribution of Brake Wear Emissions to Particulate Matter Concentrations Using a High-Resolution Brake Use Inventory, FAT-SCHRIFTENREIHE 318. Retrieved from: https://www.vda.de/de/services/Publikationen/fat-schriftenreihe-318.html.

[24] D. Wakeling et al., (2018). UK Informative Inventory Report (1990 to 2016). Department for Environment, Food and Rural Affairs (Defra), Nobel House, 17 Smith Square, London SW1P. Retrieved from: https://naei.beis.gov.uk/reports/reports?report_id=956.

[25] G. Perricone, V. Matějka, M. Alemani, G. Valota, A. Bonfanti, A. Ciotti, U. Olofsson, A. Söderberg, J. Wahlström, O. Nosko, G. Straffelini, S. Gialanella, I. Metinoz, (2018). A concept for reducing PM10 emissions for car brakes by 50%, Wear 396-397, 135-145.

[26] MATHISSEN, M., GROCHOWICZ, J., SCHMIDT, C., VOGT, R., FARWICK ZUM HAGEN, F. H., GRABIEC, T., STEVEN, H. & GRIGORATOS, T. 2018. A novel real-world braking cycle for studying brake wear particle emissions. Wear, 414-415, 219-226.

[27]Sarah Chambliss, Ray Minjares, Anup Bandivadekar. On-Board Diagnostic (OBD) Checks for Inspection and Maintenance in India. ICCT, the International Council on Cloean Trasportation, June 2016

[28]Francisco Posada, Zifei Yang, Rachel Muncrief. Review of Current Practices and New Developments in Heavy- Duty Vehicle Inspection and Maintenance Programs. The International Council on Clean Transportation, 2015, http://www.theicct.org/review-current-practices-and-new-developments-heavy-duty-vehicle-inspection-andmaintenance-programs

[29]A.J. Hickman. Vehicle maintenance and exhaust emissions. The Science of the Total Environment 146/147 (1994) 35-24

[30]Karl Hausker, Lennart Erlandsson, June Taylor, John Armstrong. Vehicle Inspection and Maintenance Programs: International Experience and Best Practices. USAID, 2004 http://pdf.usaid.gov/pdf_docs/Pnadb317.pdf

[31]Posada, F, Yang, Z, Muncrief, R. Freda Fung, Bryan Suen. A Review of the Hong Kong Inspection and Maintenance Programme for On-road Vehicleç. Civic Exchange, Aug. 2013, https://www.academia.edu/11297612/A_Review_of_the_Hong_Kong_Inspection_and_Maintenance_Programme_for_Onroad_Vehicles

[32]McCormick, R.L., Graboski, Alleman, Alvarez, Kado, Kuzmicky, Kobayashi and Duleep. Quantifying the Emission Benefits of Opacity Testing and Repair of Heavy-Duty Diesel Vehicles. Final Report to Colorado Department of Public Health and Environment, 2001

[33]Hannu Jääskeläinen. Emission Effect of Engine Faults and Service. DieselNet. Copyright ECOpoint Inc. Revision 2007.03b

[34]September 2016, PN 1565, Canadian Council of Ministers of the Environment. Vehicle and Engine Tampering Description and Examples of Acceptable Practices

[35]Nils Hooftman. uCARe, You Can Always Reduced Emissions because you care. Deliverable 1.3 Tampering. 19-12-2019

[36]Phillip Brooks. Tampering & Aftermarket Defeat Devices. Association of Air Pollution Control Agencies. August 27, 2019

[37]Frank Acevedo and Cody Yarbrough. Tampering & Aftermarket Defeat Devices. Midwest Clean Diesel Initiative Steering Committee Meeting. April 25, 2019

[38]R. J. Vermeulen, R. Verbeek, and S. Van Goethem. Mogelijkheden om manipulatie van AdBluesystemen bij vrachtwagens vast te stellen en terug te dringen – eindrapport. Den Haag, 2017.

[39]CITA, "Tampering of Emission Control Systems," in 78th GRPE- 8-11 January 2019, 2019.

[40]United States, Patent Application. Geilen et al. Patent No.: US 8,666,588 B2. Date of Patent: Mar. 4, 2014

Annex: Summary Tables of Literature Survey on Deliverable 2.1

Table 10: KPIs for Driving Behaviours

KPIs for driving behaviours	Emission	Energy	Safety
Vehicle speed distribution	X √	X √	X √
Average speed	X √	X √	
Average driving speed without stops	X	X	
% of distance in speed interval 50~70 km/h	X	X	
Acceleration distribution	X √	X √	X
Average acceleration	X	X	
% of time in acceleration	X	X	
% of distance in acceleration	X	X	
Deceleration distribution	X	X	X
Average deceleration	X	X	
% of time in deceleration	X	X	
% of distance in deceleration	X	X	
Frequency of stops	X	X	
Average stop durations	X	X	
Gear upshift speed	X	X	
Gear downshift speed	X	X	
Frequency of gear shift	X	X	
Engine speed when shifting gear up	X	X	
Frequency of improper lane change			X
Distance from other vehicles			X
Numbers of breaking traffic regulations per distance			X √
Numbers of distraction per distance during driving			X
Headways			X
Drunk driving			X
Excessive speed			X √
Fatigue driving			X
Driving in an opposite direction			X
Infrequency use of safety belt			X
Participation in car races			X
Speed difference with traffic speed			X √

Key:

- X: it is confirmed that KPIs are related to emissions/energy/safety
- √: there are equations indicating the detailed relations

Table 11: Importance ranking for KPIs of exhaust emissions and energy consumption

KPIs for Driving behaviours	Energy consumption	Emissions			
		CO	HC	NO_X	PM
Vehicle speed distribution	XXX	XX	XX	XXXX	XXXX
Average speed	XXX	XX	XX	XXXX	XXXX
Average driving speed without stops	X	X	X	XXXX	XXXX
% of distance in speed interval 50~70 km/h	XX	XX	XX	XXX	XXX
Acceleration distribution	XXXX	XXXX	XXXX	XXXX	XXXX
Average acceleration	XXXX	XXXX	XXXX	XXXX	XXXX
% of time in acceleration	XXXX	XXXX	XXXX	XXXX	XXXX
% of distance in acceleration	XXXX	XXXX	XXXX	XXXX	XXXX
Deceleration distribution	XXXX	XXXX	XXXX	XXXX	XXXX
Average deceleration	XXXX	XXXX	XXXX	XXXX	XXXX
% of time in deceleration	XXXX	XXX	XXXX	XXXX	XXXX
% of distance in deceleration	XXXX	XXX	XXXX	XXXX	XXXX
Frequency of stops	XXX	XXX	XXX	XXX	XXX
Average stop durations	X	X	X	X	X
Gear upshift speed	XX	XX	XX	XX	XX
Gear downshift speed	XX	XX	XX	XX	XX
Frequency of gear shift	XX	XX	XX	XX	XX
Average engine speed when shifting gear up	XX	XX	XX	XX	XX

Key:

XXXX: very important; XXX: important; XX: less important; X: slightly important

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Adapting driver behaviour
for lower emissions

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