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Executive summary

uCARE aims to reduce pollutant emissions of the existing European vehicle fleet. The project intends to inform drivers about how to change their behaviour in such a way that tailpipe and wear emissions are reduced. To determine possible reductions, one needs to understand how emissions are related to vehicle use.

There is much to be learned from how vehicle emissions are related to use, but to do so emission data must be stored, characterised and distributed. We propose an emission map concept with which the relationship between the use of a vehicle and experiment-based emission data can be described in a logical and structured way, be it in the form of a map or in the form of a function. Maps or functions can be created on any level of the earlier proposed vehicle taxonomy (see uCARE deliverable D1.1), dependent on distinctiveness and availability of data.

The emission maps or functions can be stored, characterised and distributed via the file exchange format proposed here. The naming of these files is based on an abbreviation of the earlier proposed taxonomy variables. The file itself contains meta-information about a vehicle or engine, as well as at least one emission map. Various other layers/augmentation maps can be included in the emission map file. The dimensions of each map can vary for each layer, dependent on which parameters best describe the emission behaviour. To handle a varying data availability among vehicle types or engine types, maps also have a flexible resolution. The map resolution selected complies to minimum standards in terms of coverage.

The emission map file distinguishes the following layers (note that not all layers need to be present in each file):

- Base layers:
 - o Tailpipe emissions under hot engine conditions: NO_x, PN, CO, HC
For these emissions, vehicle or engine speed, and CO₂ emission mass flow (as a proxy for engine power), are used as the two independent dimensions.
 - o Tailpipe emissions of non-regulated emissions: NO₂, N₂O, PAH, CH₄, cyanides, NH₃
- Augmentation layers:
 - o Tailpipe emissions under cold start conditions: NO_x, PN, CO, HC
 - o Wear emissions: particulates from brake wear, tyre wear, road surface wear
 - o Aging/maintenance: additional tailpipe emissions as a result of aging and/or poor maintenance: NO_x, PN, CO, HC, NO₂, N₂O, PAH, CH₄, cyanides, NH₃
 - o Tampering: additional tailpipe emissions as a result of tampering: NO_x, PN
 - o Retrofitting: reduction in tailpipe emissions as a result of retrofitting solutions on older vehicles: NO_x, PN
 - o Driving dynamics: the impact on tailpipe emissions due to recent driving history: NO_x, NH₃, PN
 - o *[other augmentation layers possible]*

The definition of maps and algorithms is a work in progress, and new findings from experiments may give insights not yet incorporated in the present description. At this point in the uCARE project, many activities related to development of especially the augmentation layers are still ongoing. How exactly the augmentation layers interact with the base layers will follow from these developments.

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Definitions & Abbreviations

AEM	Augmented Emission Map
ASCII	American Standard Code for Information Interchange
CADC	.....	Common Artemis Driving Cycle
CAN	.....	Controller Area Network
cm ³	.....	Cubic centimetre
CO	.....	Carbon monoxide
CO ₂	.....	Carbon dioxide
COPERT	.....	Computer Programme to calculate Emissions from Road Transport
DGR	.....	Directorate-General Research
DOI	.....	Digital Object Identifier
DoW	.....	Description of Work
EC	.....	European Commission
ECU	.....	Engine control unit
e.g.	.....	Example given
EGR	.....	Exhaust Gas Recirculation
ERMES	.....	European Research Group on Mobile Emission Sources
etc.	.....	Et cetera
FTIR	.....	Fourier-transform Infrared Spectroscopy
HBEFA	.....	Handbook Emission Factors for Road Transport
HC	.....	Hydrocarbon

ICE	.....	Internal Combustion Engine
i.e.	.....	Id est
ISO	.....	International Organization for Standardization.
IUFC	.....	Inrets urbain fluide court (a driving cycle to measure cold start emissions)
LNG	.....	Liquified natural gas
LPG	.....	Liquified petroleum gas
NEDC	.....	New European Driving Cycle
NH ₃	.....	Ammonia
NO	.....	Nitrogen monoxide
NO ₂	.....	Nitrogen dioxide
NO _x	.....	Nitrogen oxide
OBD	.....	Onboard Diagnostics
PAH	.....	Polycyclic aromatic hydrocarbons
PEMS	.....	Portable Emissions Measurement System
PHEM	.....	Passenger Car and Heavy Duty Emission Model
PM	.....	Particle Mass
PN	.....	Particle Number
RDE	.....	Real Driving Emissions
RFC	.....	Request for Comments
RMSE	.....	Root-mean-square error
RPM	.....	Revolutions per minute
SCR	.....	Selective Catalytic Reduction
SEMS	.....	Simplified emission measurement system
WLTP	.....	Worldwide Light Duty Test Procedure
WP	.....	Work Package

1 Introduction

1.1 Background uCARE

With four million people dying annually due to outdoor pollution, improvement of air quality has become one of society's main challenges. In Europe, traffic and transport have a large effect on air quality, specifically passenger cars and commercial vehicles, and to a lesser extent non-road mobile machinery. While technical improvements and more stringent legislation have had a significant impact, traffic and transport emissions are still too high and air quality is still poor. Although the use of electric and other zero-emission propulsion technologies may drastically reduce the pollutant exhaust emissions from traffic, the slow introduction of such vehicles as well as the trend of increasing vehicle lifetimes means that vehicles with internal combustion engines are expected to dominate the fleet beyond 2030. This project is the first opportunity to improve emissions of vehicles, not by improving vehicle technology, but by actively involving vehicle users and enabling their contribution to clean driving.

So far, expertise on pollutant emissions has mainly been used to advise European policy makers on limited effectiveness of emission legislation (through real-world emission factors such as HBEFA and COPERT) and how to reduce traffic and transport pollutant emissions. The numerous mitigation methods are rarely extended to include the perspectives of users, thus uCARE enables a next essential step: providing user targeted emission reduction measures. These measures will be implemented and evaluated in real-life pilot projects.

The aim of uCARE is *to reduce the overall pollutant emissions of the existing combustion engine vehicle fleet by providing vehicle users with simple and effective tools to decrease their individual emissions and to support stakeholders with an interest in local air quality in selecting feasible intervention strategies that lead to the desired user behaviour*. The overall aim is accompanied by the following objectives:

1. To identify **user-influenced vehicle emission aspects** (such as driving behaviour and vehicle component choice).
2. To determine the **emission reduction potential** of each vehicle emission aspect with help of the uCARE model developed within a toolbox.
3. To develop a **toolbox**, containing models and emission reduction measures, that enables stakeholders to identify the most appropriate intervention strategies that reflect the specific users and their motivation.
4. **Support policy makers** and other **stakeholders with an interest in air quality**, such as municipalities and branch organizations, **in identifying intervention strategies** that translate the measures into desired behaviour of the user.
5. **To test and evaluate** intervention strategies in a set of pilot projects conducted with various target user groups in at least four European countries. The pilot projects illustrate effectiveness and feasibility of the toolbox and intervention strategies developed on its basis.
6. Perform an **impact assessment** of the intervention strategies effectiveness, in terms of cost, penetration, achieved emission reduction and lasting effects.
7. **Actively feed** European cities and international parties with uCARE learning and results, via awareness raising campaigns, communication tools, interactive web application and other dissemination activities. Open access to the broad public to the toolbox, data and developed tools.
8. Summarise the findings **in blueprints for rolling out** different user-oriented emission reduction programmes, based on successful pilots.

This document is part of WP1 and describes the Augmented Emission Maps, which are part of the collection of standardized data in the uCARE toolbox.

1.2 Purpose of the document

For a range of car models and makes uCARE will produce and publish emission maps, using the clustering of the uCARE Taxonomy as described in deliverable D1.1. The objective of this document is to provide the metadata to correctly interpret and use the emission maps.

1.3 Document Structure

The remainder of the document is structured as follows.

Chapter 2 describes the Augmented Emission Map (AEM) concept. An AEM can be made for each node in the uCARE Taxonomy¹ (D1.1) and it is explained how the AEMs and the taxonomy are linked. The file name conventions for AEMs are also defined in chapter 2.

Chapter 3 explains the approach of emission maps: data-based and with layers corresponding to the different types of emissions: hot engine tailpipe emissions, cold start tailpipe emissions, non-regulated tailpipe emissions, wear emissions, etc. This chapter also discusses the quality assurance of the AEM and the effects of vehicle dynamics on NO_x emission maps.

Chapter 4 shows a range of example AEMs and discusses the proper interpretation.

The idea behind the AEMs is that they can be used to define an exchange format for emission data. Chapter 5 is devoted to the definition of this exchange format.

Finally, chapter 6 draws the conclusions regarding the current status of the AEMs as a standard for emission data exchange. Such standards are never static and may be refined and expanded.

1.4 Deviations from original Description of Work (DoW)

1.4.1 Description of work related to deliverable as given in DoW

“This document provides a description of the functionality of augmented emission maps and a reference to the open-source website containing the augmented emission maps information for the relevant vehicle groups and technologies in the taxonomy.”

1.4.2 Time deviations from original DoW

The document was planned to be delivered end of January 2020. The submission was slightly delayed after agreement with the Project Officer to allow for production of a first batch of AEMs in parallel to this document.

1.4.3 Content deviations from original DoW

None

It should be noted that a document like this is in development, describing a standard to be applied in the entire uCARE project and possibly beyond in emission simulation. It is foreseen to be updated later in the uCARE project.

¹ The vehicle taxonomy is a controlled vocabulary and vehicle classification system for all passenger cars on the road

2 Introduction emission maps

2.1 Concept of emission maps

In uCARe the target is a reduction of pollutant emissions from the existing European vehicle fleet. This shall be achieved by informing drivers how to change their behaviour in such a way that tailpipe and wear emissions are reduced. The first step then is to understand how emissions are related to the use of the vehicle, caused by driver behaviour.

The emissions of a vehicle are first and foremost linked to the characteristics of the vehicle: fuel type, emission standard, engine block, exhaust gas treatment technology, weight of the vehicle, and more. To characterise and categorise vehicles, a taxonomy has been developed (deliverable D1.1). Emission behaviour can be related to different levels in the taxonomy, e.g. euro class or engine block, and using the taxonomy, the empirical emission data can be attributed to groups of vehicles that share a taxonomy code (e.g. all vehicles fitted with a 1242 cc petrol engine of make X, or all euro 6 petrol vehicles). Thereby it is assumed that all vehicles in the same taxonomy group have similar emission behaviour. Hence it is important to wisely choose the level of the taxonomy that our insights in emissions are attached to. Emission data is in limited supply, but attributing the same emission behaviour to a group of technologies too diverse, can lead to large uncertainties. More about the link to the taxonomy can be found in paragraph 2.2.

Secondly, the emissions are linked to the state of the vehicle: maintenance and tampering. Delayed maintenance can lead to (gradually) increased emissions, tampering can undo the effect of emission treatment, leading to unabated levels.

Knowing the vehicle's characteristics and the state of the vehicle, a 'window' is left within which emissions can vary due to the way the vehicle is used. For each emission component the relation between emission level and use is different. For instance, nitrogen oxide levels are known to correlate well to the engine speed and the amount of power the engine has to deliver. The emissions of tyre wear, on the other hand, are related to the weight of the vehicle, cornering speed, braking/acceleration, and external factors such as road surface types and weather conditions

Based on measurement data of the key parameters, a map of the emission levels can be made. For nitrogen oxides (NO_x), for example, the map could depict engine speed on the x-axis, the amount of power on the y-axis, and the NO_x emissions in mg/s as a colour. Figure 2.1 shows an example of such a map for a random vehicle/group of vehicles. Note that CO₂ emission is used as a proxy for power².

² The CO₂ flow in g/s is proportional to the fuel flow, i.e. energy delivered per time, i.e. the power content of the fuel.

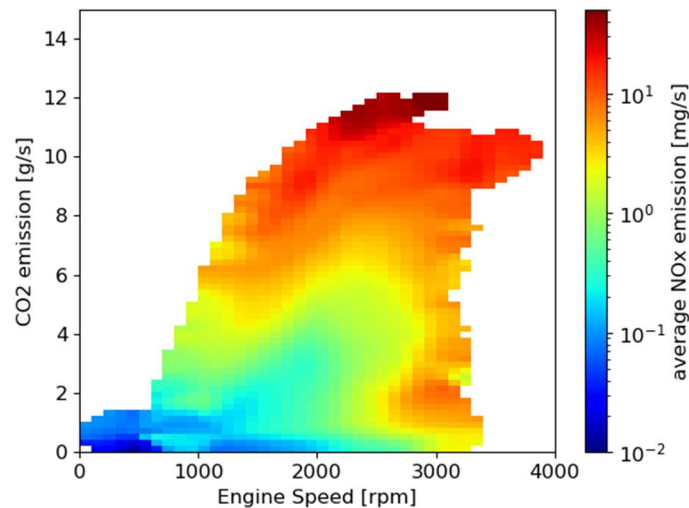


Figure 2.1 Example emission map for average NO_x emission from a Euro 6 diesel engine

During driving, the engine speed and CO₂ output vary almost continuously. This means that the vehicle 'runs' across the map. Instantaneous emissions can thus be predicted on a second-by-second basis.

The map shows that for this vehicle category, if a driver presses the accelerator pedal at mid to high engine speed, the emissions are high (top of the graph). Also driving with high engine speed and relatively low power, the emissions are high (right hand side of the graph).

To be able to create such a map, measurement data is needed for the entire spectrum of engine use, from at least one vehicle representative for the taxonomy code. Furthermore, interpolation algorithms are needed to fill the map if gaps occur. Also it may be necessary to reduce the map resolution if a limited amount of data is available. Generally speaking, boundary conditions have to be set to warrant a minimum quality and usefulness of the emission maps produced. This will be discussed in chapter 3.

Maps will be generated not only for NO_x. Chapter 3 contains a discussion of all envisaged emission map layers.

2.2 Link with vehicle taxonomy

The vehicle taxonomy is a controlled vocabulary and vehicle classification system for all passenger cars on the road. As described in D1.1 it has 11 levels; two parts can be distinguished: the vehicle part and the engine part. The engine is a child of the vehicle. The vehicle code contains the make and model, the transmission type, all-wheel drive capability and the battery capacity. An example of the first three levels is shown in Figure 2.2.

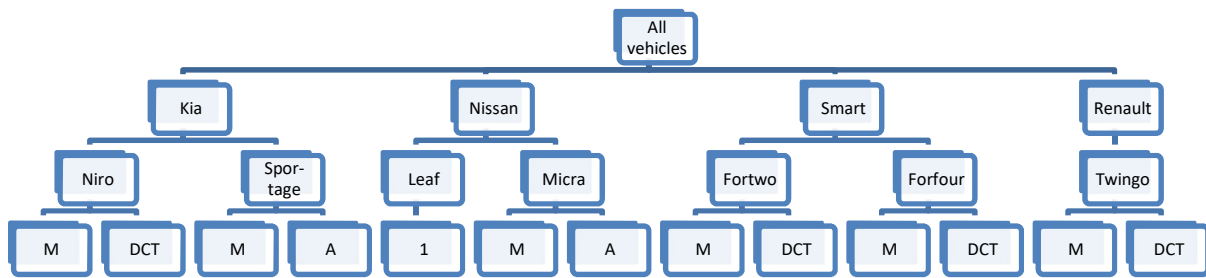


Figure 2.2 Example of vehicle part of taxonomy: first three layers. Gearbox layer: M=manual, A=automatic, DCT=dual clutch transmission, 1=single speed

Tyre and road wear characteristics, at least, can be linked to the vehicle code, because the vehicle code is related to the weight (and driver behaviour). Most emission characteristics are related to the drivetrain though. Each vehicle model/gearbox combination in the example can be fitted with one or more engine types (or traction motor types for electric vehicles). However, engines can be used across multiple manufacturers. In fact, of the seven vehicle models in Figure 2.2, the four rightmost ones can be fitted with the same “M281” engine, and should have similar NO_x emissions at equal power demand and engine speed³.

Engines are characterised by the other six variables in the taxonomy:

- Powertrain type (e.g. ICE, electric)
- Fuel type (e.g. petrol, electricity)
- Emission standard (e.g. Euro 6)
- Engine displacement (e.g. 1598 cm³)
- Engine power (e.g. 66 kW)
- Manufacturer alliance

The list of manufacturer alliances is provided in D1.1. It is intended to avoid having double entries of the same engine. The engine specifications (the combination of the first five variables) typify the alliance code in 95% of the cases; a lookup table will be provided. For the other 5%, the vehicle manufacturer provides a definitive answer; this list will also be provided.

Figure 2.3 shows an example of the hierarchy of engine specifications. The 1-liter versions of the four rightmost vehicles in Figure 2.2 share the same alliance code: RNM3 - Renault-Nissan-Dacia-Smart.

³ Provided the engine calibration and ECU parametrization is identical, for a given engine used in different vehicle models and furthermore that vehicles had timely maintenance and have similar mileage.

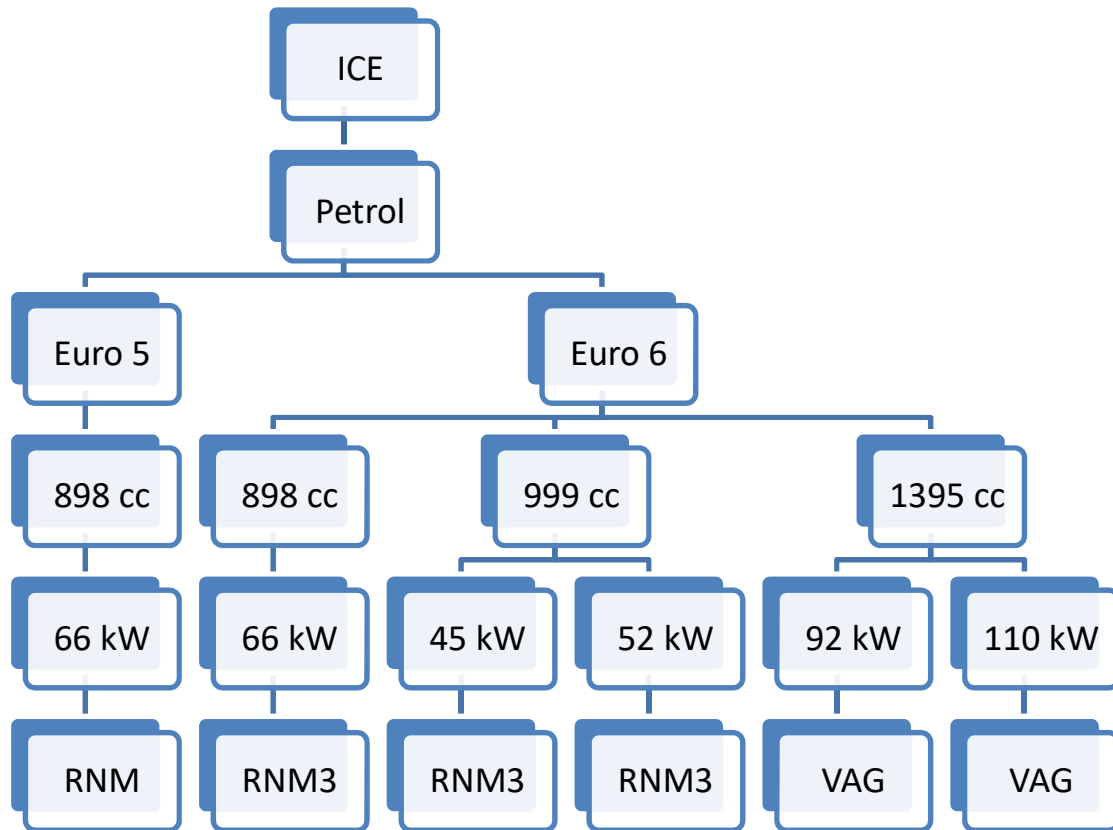


Figure 2.3 Example of engine part of taxonomy

2.3 Naming conventions

A data file structure was proposed to simplify the exchange of emission map data, see chapter 5. At the moment, all map layers, except wear emissions, are related to the internal combustion engine of a vehicle (see chapter 3). Therefore the naming scheme of the emission map files will be related to the engine part of the taxonomy. Hereafter an abbreviation is proposed for practical reasons. Wear emissions are related to vehicle properties rather than engine properties. Wear emission maps will be distributed with their own naming scheme.

0. Powertrain types: not included in the name

The emission maps always refer to the internal combustion engine part of a vehicle, even if there is an electric drivetrain as well. The powertrain type as a variable is not needed to characterise the ICE, and in fact would create redundant data. Therefore it is left out of the file name.

1. Fuel types

The following translation is made, see Table 2.1.

Table 2.1 Fuel type coding

Fuel type as D1.1	Fuel type abbreviation
Diesel	D
Petrol	P
Electricity	E
Ethanol (E85)	A
CNG	C
LPG	LP
Hydrogen	H
Biodiesel	BD

The letter L is reserved for LNG, should the scheme be extended to other vehicle categories.

2. Emission standards

The translation can be found in Table 2.2. The breakdown of Euro 6 was done because real-world emissions have changed significantly in Euro 6d-Temp and Euro 6d.

Table 2.2 Emission standards coding

Emission standard as D1.1	Emission standard abbreviation
Euro 0	0
Euro 1	1
Euro 2	2
Euro 3	3
Euro 4	4
Euro 5	5
Euro 6a	6a
Euro 6b	6b
Euro 6c	6c
Euro 6d-Temp	6dT
Euro 6d	6d

3. Engine displacement

The displacement is included without unit, in cubic centimetres.

4. Rated power

The rated power is included without unit, in kW.

5. Manufacturer alliance

The manufacturer alliance codes and the names of associated manufacturers are listed in Annex B.

The parts of the name are connected by underscores.

Example:

The engine block on the left-hand side of Figure 2.3 will have the following filename:

P_5_898_66_RNM

2.4 Analysis of the Netherlands vehicle fleet

In the Netherlands, as of 22 January 2020, around 9.7 million passenger vehicles are registered in the Dutch vehicles database. Analysing the composition of the passenger vehicle fleets, Volkswagen is the most common brand (11.4% share of the total fleet), with Volkswagen Golf and Polo as the most common models.

Based on the Open Data from the vehicles database of the Dutch type approval authority RDW (opendata.rdw.nl), the uCARE engine family code can be derived and assigned to (almost⁴) every registered vehicle.

For the vehicles with complete information, uCARE engine family codes are assigned and analysed. The most popular uCARE engine family in the Netherlands belongs to petrol vehicles with a 998 cc engine with a rated power of 50 kW from the Toyota-Citroën-Peugeot alliance. This uCARE engine family code is associated with small passenger vehicles such as the Toyota Aygo. This engine family has two variants based on the emission standards coding, 1.9% has Euro 4 emission standards while 1.4% has Euro 5 emission standards.

Figure 2.4 shows the top 10 uCARE engine families registered in the Netherlands, which together are fitted in 8.3% of the passenger car fleet in the Netherlands.

⁴ For 6.5% of the vehicles one or more parameters are missing. Generating the engine family code for these vehicles would require some additional work.

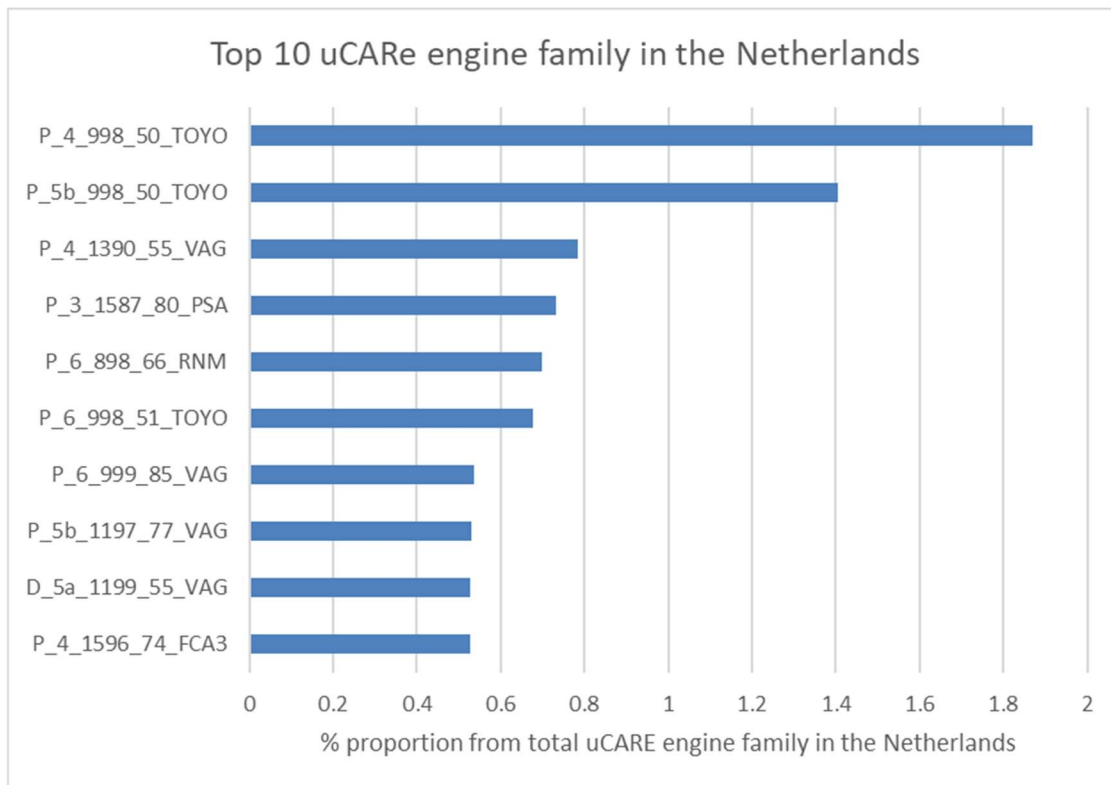


Figure 2.4 Top 10 uCARE engine family for passenger vehicles registered in the Netherlands

3 Approach

3.1 Design of augmented emission maps

3.1.1 Content

Augmented emission maps should be fact-based. It was therefore agreed in the uCARE project to fill the distributable emission map files with data backed values only. If gaps do occur in the emission map, the end-user has the freedom to choose a suitable interpolation method to fill in the gaps before further analysis or usage of the map. A script will however be provided by the uCARE team to process the emission maps. The script will take care of interpolation and smoothing of the maps.

For some map layers, it may be chosen to implement the emission maps as a continuous function instead. Parameter values to insert into the function can then be distributed per vehicle (class) in the same way maps are distributed. The function is then implemented on the tool side.

The descriptions below refer to the distributable, fact-based maps and functions. We note that, in this report, we focus primarily on the proposed structure of the AEMs. The precise content and applicability of the various augmentations is still a work in progress.

3.1.2 Base Layer and Augmentation Layers

Isolated effects of different conditions and emission sources are expressed in separate layers, together forming augmented emission maps: all layers characterize parts of the emission behaviour of the vehicle.

The tailpipe emissions under hot engine conditions are set as the **base layer** for the emission maps. Tailpipe emissions are used as the base layer for two main reasons. Firstly, and most importantly, tailpipe emissions are the emissions with the most impact on the environment. Secondly, with regards to the data-based nature of the emission maps, most tests and monitoring programs collect tailpipe emission data. Current base layers would describe NO_x (primary focus), PN, CO, and HC emissions. Other base layers could include tailpipe emissions of non-regulated emissions: NO₂, N₂O, PAH, CH₄, cyanides, and NH₃.

On top of the base layers, the following **augmentation layers** are currently proposed:

- Tailpipe emissions under cold start conditions: NO_x (primary focus), PN, CO, HC
- Wear emissions: particulates from brake wear, tyre wear, road surface wear
- Aging/maintenance: additional tailpipe emissions as a result of aging and/or poor maintenance: NO_x, PN, CO, HC, NO₂, N₂O, PAH, CH₄, cyanides, NH₃
- Tampering: additional tailpipe emissions as a result of tampering: NO_x, PN
- Retrofitting: potential reduction in tailpipe emissions as a result of retrofitting solutions on older vehicles: NO_x, PN
- Driving dynamics: the impact on tailpipe emissions due to recent driving history: NO_x, NH₃, PN

Each map layer can have a different x- and y-axis, a different resolution and a different level in the taxonomy to be attached to. The layers are discussed separately hereafter.

3.1.3 Dealing with data availability limitations

Emission map layers described below rely on test data. Extensive real world test data are not available for all engines or vehicles. The goal is to produce maps for as many vehicles/engines as possible, also for those for which limited data is available. Five levels of data availability can be distinguished:

Level 1: Monitoring data of real-world driving (several hours up to several years). Data can be binned and averaged and converted into a map. In this conversion it is important that

sufficient data is available for all the situations (combinations of variable values) that occur in real-world driving. Monitoring data can be collected using PEMS, SEMS or OBD-loggers using vehicle sensor data.

Level 2: Chassis dynamometer modal mass data from real world cycles (CADC, ERMES, WLTP up to EURO 6b⁵). Second-to-second concentration data is available for many engine types. Test cycles generally cover a limited part of the vehicle/engine use area. Representative real world cycles however, shall cover most of the relevant engine operation areas. Maps may have to be reduced in resolution, due to the shorter test duration compared to level 1 and the resulting smaller amount of instantaneous data available to fill the maps.

Level 3: Manufacturer test cycle data/bag data; RDE, CADC. For engines for which only this data is available, the emission maps will hold only a few data points (urban, rural and motorway driving). In some occasions it is necessary to revert to such a simplified map to be able to give an indication of emission levels.

Level 4: Experiment based models. If test data is not readily available, it may be an option to base emission level estimations on findings from experimental research. For instance, to convert tyre test data to vehicle use related wear, the relation between e.g. speed and wear can be determined by experiments and in-lab simulations.

Level 5: Physics based models. Emissions can be predicted by modelling the behaviour of e.g. engine, aftertreatment, tyres and brakes.

3.2 Base Layer - Hot engine tailpipe emissions

Tailpipe emissions for a given vehicle can generally be related to engine speed and engine load, and, related to the aftertreatment for Euro 6 diesel vehicles, a historic component describing the temperature level of the SCR system. Vehicles with the same engine/exhaust gas aftertreatment combination should have similar emission behaviour with respect to the hot emissions layer. Therefore the full engine block code is chosen as the distinguishing identifier. Aftertreatment behaviour is highly software dependent, so this does warrant further investigation.

The emission maps are intended to be used in tools that simulate emissions of trips, e.g. to evaluate the improvement potential by changing driver behaviour. Vehicle speed profiles can be produced in many ways, without the necessity to read data from the vehicle's CAN bus. In order to also be able to share this data, a second design option will also be implemented for the hot emissions layer, based on vehicle speed instead of engine speed. Note that the actual emissions at a given speed depend on the selected gear, which means that the map based on vehicle speed cannot represent all situations.

Engine load, the second parameter, is not always available either. The CO₂ emission rate is chosen as the y-axis, as CO₂ is a good proxy for the engine power demand which will vary with acceleration, payload, road slope and wind. In the case of limited data (test cycle data only), the CO₂ emission can be estimated by estimating 'power' using payload and test cycle characteristics such as velocity profile with the equations of vehicle longitudinal dynamics.

The first maps depict NO_x and are based on the TNO monitoring program⁶ of a Volkswagen Caddy (2018), see Figure 3.1. The graph on the left-hand side has engine speed as an x-axis, the one to the right is based on vehicle speed.

⁵ It is intended not to use data from type approval tests (NEDC up to EURO 5 and WLTP from EURO 6 d-temp on). Engines are usually optimised for low emissions in type approval tests and thus maps from such cycles are not necessarily representative for real driving.

⁶ Measurements were done using the Smart Emissions Monitoring System (SEMS) [1]

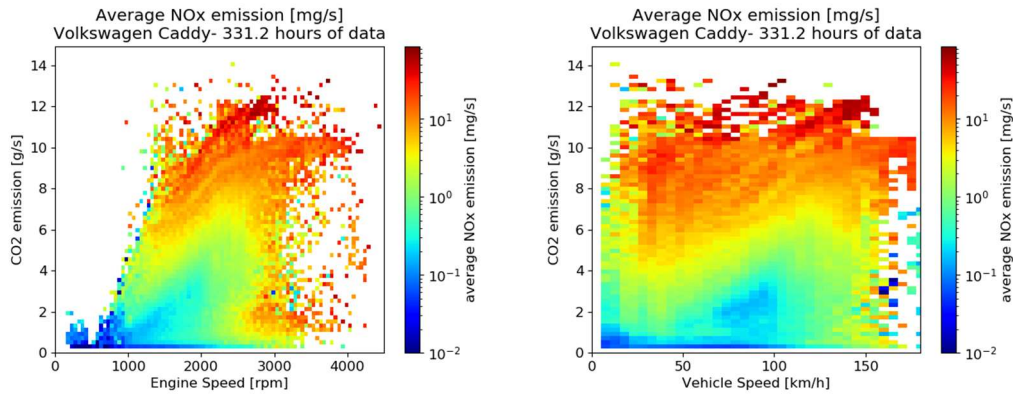


Figure 3.1 Emission map of average NO_x mass flow of Volkswagen Caddy 2018, based on over 300 hours of driving data

The explanation of how to use the map was given in paragraph 2.1 .

Similar maps can be made for PN, CO and HC. Figure 3.2 shows an example of a CO map.

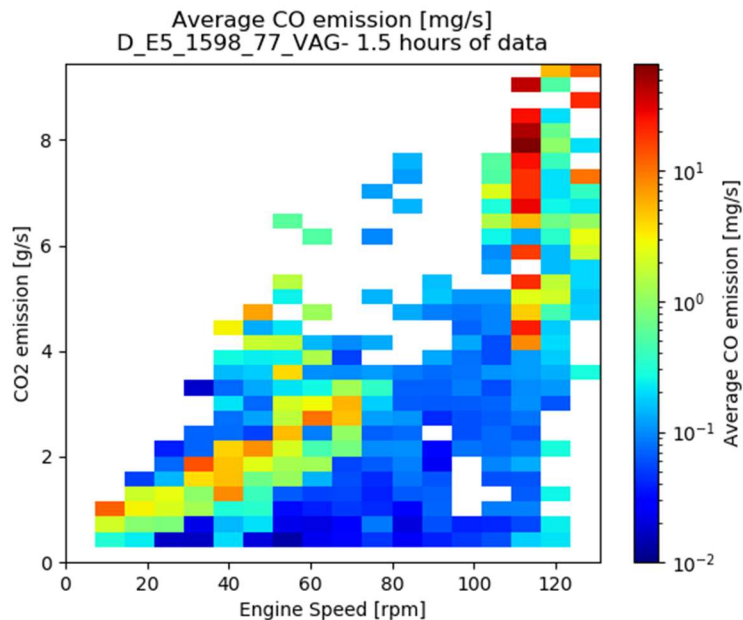


Figure 3.2 Emission map of average CO emission mass flow of Ford Fiesta

Emission maps of this design can be created for each engine block. However, for most engine blocks less than 300 hours of data is available. This does not have to hamper the usability of the emission maps, as long as map coverage is warranted and the resolution is adjusted in an appropriate way. Mathematical solutions to this end are described in paragraph 3.3.6.

3.2.1 Non-regulated tailpipe emissions

Emissions of NO₂, N₂O, PAH, CH₄, cyanides and NH₃ can be mapped over the most suitable variables, based on chassis dynamometer tests where more extensive analyser equipment is used (e.g. FTIR). PEMS tests usually record, additionally to NO_x, also NO and NO₂ separately. An example NH₃ map (based on CO₂ and vehicle speed) is shown in Figure 3.3. Note that this may not be the final design for the NH₃ emission maps.

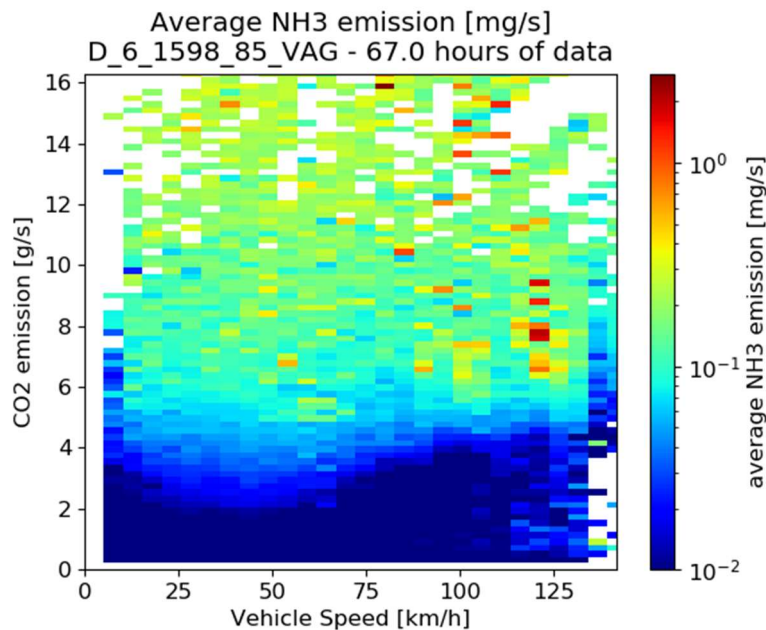


Figure 3.3 Emission map of average NH₃ mass flow of a diesel vehicle with 1598 cc 85 kW VAG engine, based on 67 hours of driving data

3.3 Augmentation Layers

Augmentation layers are used to augment the data provided by the base layers. Initial proposals for these layers address a range of conditions (influenceable by the user) which can effect vehicle emissions. These initial proposals will be developed further, and reported on in more detail at a later date.

3.3.1 Cold start tailpipe emissions

A model is being developed to determine the cold start extra emissions of CO, HC, NO_x and particle number (PN). The resulting emissions are additional to the hot emissions, and form a continuous function in time over the cold start period. Further description of the current state of the model of the cold start effect can be found in Annex D.

3.3.2 Wear emissions

There are no regulations and no standardized test methods for determining wear emissions to build upon. For now, the focus will be on tyre wear. Tyre wear is influenced by the load, torque, the type of tyre, the dimensions, the inflation pressure of the tyre, wheel alignment, age, vehicle speed, acceleration/deceleration and cornering speeds. Within uCARE, experimental data (Level 4 in paragraph 3.1.3) will be gathered for the parameters load, type of tyre, vehicle speed and inflation pressure. This is done under the assumption that total wear is proportional to the PM emission.

The function to be derived from the experimental work will not be bound to a vehicle type, but to the type of tyre and driving characteristics. After finalising the experimental work it will be decided whether wear data will be shared in a map form or in the form of a function and vehicle/use parameters.

Also brake wear is analysed if a function can be derived from measured data to show brake wear as function of brake power and/or brake energy. So far the available data is very limited.

3.3.3 Aging/maintenance

Aging effects are described e.g. in a 2019 report by IVL: Study on the durability of European passenger car emission control systems utilizing remote sensing data. The work on aging will be built on top of the work described. It is planned that a linear equation for the emission deterioration (% change versus a new car) as function of vehicle mileage will be used. The effects of improper or insufficient maintenance are not covered in the existing report, but should be implemented in uCARE.

3.3.4 Tampering

Tampering effects are described in uCARE deliverable D1.3 by Nils Hooftman, dated December 19, 2019. Implementation into the AEMs will follow.

3.3.5 Retrofitting

The effectiveness of retrofit emission control devices will be considered by conversion efficiency maps in the format of the augmented maps. Since no retrofit systems have been measured yet, the currently proposed approach has not been tested yet and may still be adjusted. First test data is expected from a project from DGR, which tests 4 SCR retrofit systems.

It is currently proposed that the tailpipe emissions for retrofitted cars can be calculated for each grid point in the emission map simply by following equation:

$$E_{\text{retrofit}} = E_{\text{base}} * (1 - E_{\text{tac}})$$

With:

E_{base} emission value of exhaust component "E" in the augmented map

E_{retrofit}emission value of exhaust component "E" for a vehicle with retrofit of the device "C"

E_{tac} reduction efficiency of a retrofit system (e.g. 0.75 for a retrofit SCR with 75% conversion efficiency at a given map point)

3.3.6 Dynamic effects

For a number of different emissions, most notably NO_x, recent driving history/dynamics also influences instantaneous emissions. The tailpipe emissions at a given time are affected by:

- 1) Short transient load changes within ca 3 seconds, which influence engine out emissions, due to transport time delays in the air path, inertias and calibration issues of engine components (leading e.g. to turbo charger lag, EGR and lambda variabilities, etc.).
- 2) Long-time engine load levels, influencing the NO_x aftertreatment (=SCR) temperature. The SCR temperature follows the exhaust temperature with delay due to the thermal inertia of the exhaust system. Thus e.g. a short low load phase with exhaust gas temperature of ca 150°C is no issue, the SCR temperature may drop from e.g. 250°C to 240°C and SCR is still operating reasonable well. If low load is driven longer, the SCR temperature reaches the 150°C exhaust temperature and the SCR efficiency approaches zero. This effect results from several minutes of engine operation state before an emission event.

An initial attempt is made to make an overlay emission map with emission levels taking place during short transient load changes, which is described in Annex C. This investigation is on-going.

3.4 Quality assurance and indication of uncertainty

3.4.1 Introduction

The generated emission maps are mainly based on the average of the measurement data per bin. The standard deviation, 25th and 75th quartile are also provided within each emission map. These parameters give an indication of the variation of data inside each bin in the emission map.

Further investigation is needed as to the precise consequences of how the data is binned. One option is to implement a variable bin size algorithm during emission map generation, as described in the next section. At the moment, there is no restriction on the required minimum data inside each bin included in the algorithm. This means that bins with 1-second data are still considered as valid data points. This no-restriction does help to preserve as much data as possible to be included in the emission map. However, further evaluation is needed if it is necessary to set a threshold of minimum data per bin for the implementation of the algorithm.

3.4.2 Variable bin size

To be able to create emission maps for (nearly) all vehicles/engines, we need to deal with the varying availability of measurement data. If the amount of the data is too limited, an emission map with a fixed bin size will be too sparse to visualize the emission trends of the vehicles. Furthermore, variability resulting from missing data could be interpreted as "real" variation if a bin size is used which is too small. A proposed solution to solve this issue is to automatically determine the bin size of the emission map based on the amount of data available. By enlarging the bin size, variability within a bin can indeed be interpreted as such. Note that this holds mainly for the tailpipe emission maps.

3.4.2.1 Description of algorithm

The algorithm used to determine the bin size is formulated by calculating the ratio of the maximum area of the island of pixels in the emission map, and the total count of non-zero pixels⁷ (will be referred as coverage ratio). In other words

$$\text{coverage ratio} = \frac{\text{Area}_{\text{island with maximum area}}}{\sum \text{Area}_{\text{all islands}}}$$

An island of pixels is defined as a cluster of contiguous non-zero numbers in a sparsely populated matrix. For example, assuming that the emission map is an image that has the dimension of 4 x 4 pixels, and the bin size is set as 1x1 pixel (denoted by the black-dashed square), the emission map can be simplified as a 4x4 matrix as follows:

$$\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \end{bmatrix}$$

Note that the ones represent the *existence* of data in the pixel and not the *amount* of data in each pixel.

In this example, the maximum area of the island of the pixels is 3, shown by the red bracket and the total area of non-zero pixels (or the total area of all the islands) is 6. The coverage ratio is $\frac{3}{6}$, or 50%. If the threshold of the acceptable coverage ratio is set to 90%, this case would not meet the threshold. The bin size of the emission map would then be enlarged and the emission map regenerated.

Assuming the bin-size is increased to 2x2 pixels, as denoted by the black-dashed square, the matrix above will be divided into 4 bins. The matrix can therefore be reduced into a 2x2 matrix to note the existence of data in the enlarged pixel, shown by the right matrix.

$$\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \end{bmatrix} \rightarrow \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}$$

The maximum area of the island of the pixels in the right matrix is 3, shown by the red bracket. The total area of non-zero pixels is also 3, so the new coverage ratio is $\frac{3}{3}$, or 100%. The 2x2 pixels (as indicated by the black dashed line) will be the final bin size to be used to plot the emission map.

3.4.2.2 Implementation of algorithm to emission map

The algorithm above is implemented to the two emission maps of NO_x emissions (one with engine speed and one with vehicle speed on the x-axis).

In the creation of each emission map, the algorithm will start with the smallest bin size: vehicle speed 5 km/h per bin, CO₂ emission 0.2 g/s per bin, and engine speed 50 RPM per bin. Currently, the threshold for the acceptable coverage ratio is set at 90%.

If the starting coverage ratio is equal or larger than 90% (i.e. sufficient measurement data to cover the emission map), the starting bin size is chosen. The algorithm will not try to decrease the bin size further than the starting values.

If the starting coverage ratio is smaller than 90%, the bin sizes are scaled by the square root of 2. For example, in the vehicle speed-based NO_x map, the bin size for vehicle speed will be scaled from 5 km/h to 7.1 km/h (and further to 10 km/h if necessary) and the bin

⁷ Note that this means that a pixel is counted as covered if it has at least one data point.

size for CO₂ emission will be scaled from 0.2 g/s to 0.28 g/s (and further to 0.4 g/s if necessary). The value square root of 2 is chosen to control the speed of the resolution change.

3.4.2.3 Example case: Skoda Octavia with 11 hours of measurement data

Data from a Skoda Octavia was collected from RDE (Real Driving Emissions) tests. Note that this is still Level 1 in paragraph 3.1.3. Using the algorithm above, the starting coverage ratio is calculated to be 64.4%, which is below the threshold value.

The algorithm increases the engine speed resolution incrementally from 50 RPM to 141 RPM and CO₂ emission resolution from 0.2 g/s to 0.57 g/s, where the final coverage ratio is calculated to be 97.1%. Figure 3.4 shows the comparison between the emission map with the starting smallest size (left figure) and the enlarged bin size (right figure).

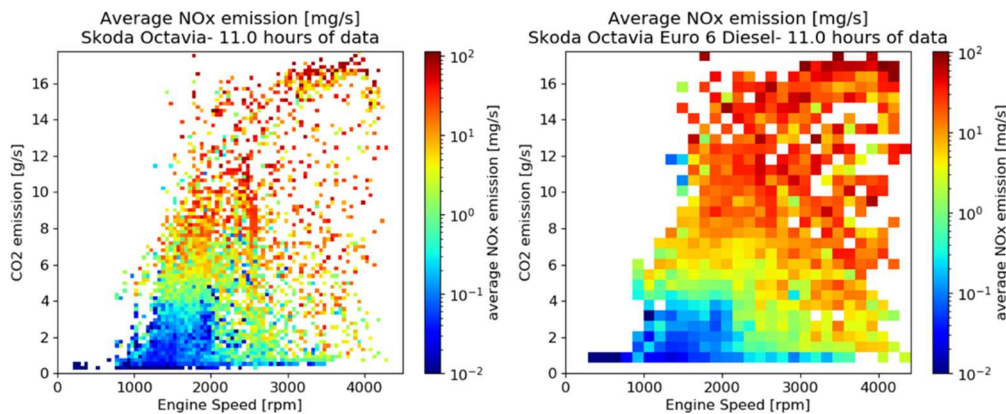


Figure 3.4 Comparison of NO_x emission map with the smallest bin size (left figure) and enlarged bin size (right figure) after the algorithm is applied.

The flexible bin size algorithm will affect the resolution of the emission map. As a result, if the generated emission map is directly used as a tool for predicting the NO_x emission of the vehicle, the accuracy of the prediction can be effected.

As an example case, the maps generated from Figure 3.4 are directly used to build a 2D lookup table for predicting NO_x emission from the same vehicle. Any empty bins are directly filled with 0s for simplicity. Any further processing or aggregation are left to the end users for to apply for their own intended purpose, and is not discussed in this section.

When calculating the Root Mean Square Error (RMSE) between the measurement data and the prediction models, the NO_x prediction using the smallest bin size is 4.17 mg/s while using the enlarged bin size is 4.32 mg/s. However, looking at the second by second data shown in Figure 3.5, the difference between the predicted and measured NO_x value is more stable in the case of the enlarged bin size, as shown in Figure 3.6.

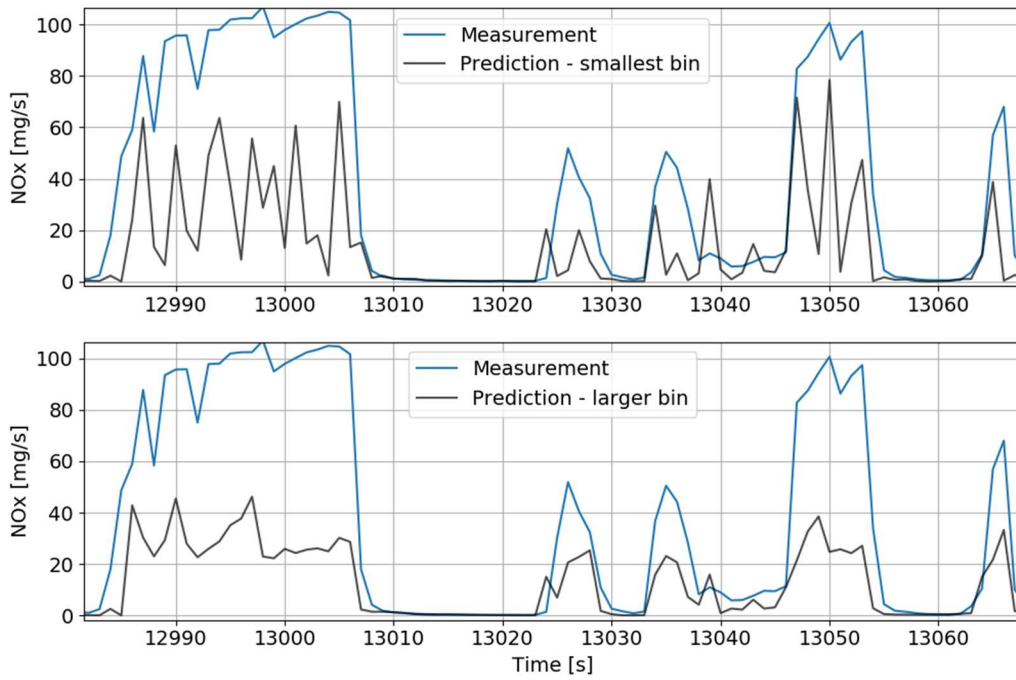


Figure 3.5 Example case on directly predicting NO_x with the emission map with smallest bin size (top figure) vs enlarged bin size (lower figure).

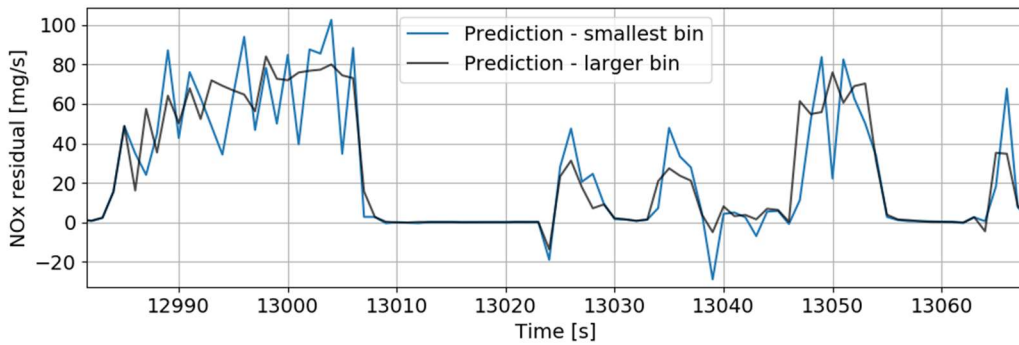


Figure 3.6 Plot of NO_x residuals from Figure 3.5

4 Emission map results

Monitoring the emissions of vehicles gives a good coverage of the whole operation spectrum of an engine. Figure 4.1 shows a graph of a NO_x emission map which is based on more than 600 hours of on-road measurement data of a Euro 6 diesel car. The average NO_x emission is shown per bin of vehicle speed and CO₂ emission. Figure 4.2 is based on the same data but shows the average NO_x emissions per engine speed and CO₂ emission bin.

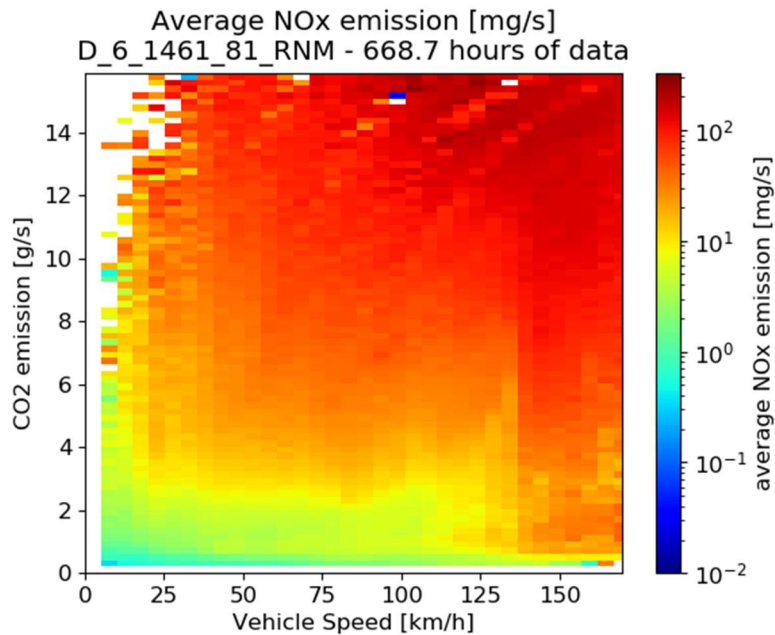


Figure 4.1 Emission map graph of a 1461cc, 81kW Euro 6 Diesel engine with average NO_x emission [mg/s] per speed [km/h] and CO₂ [g/s] bin.

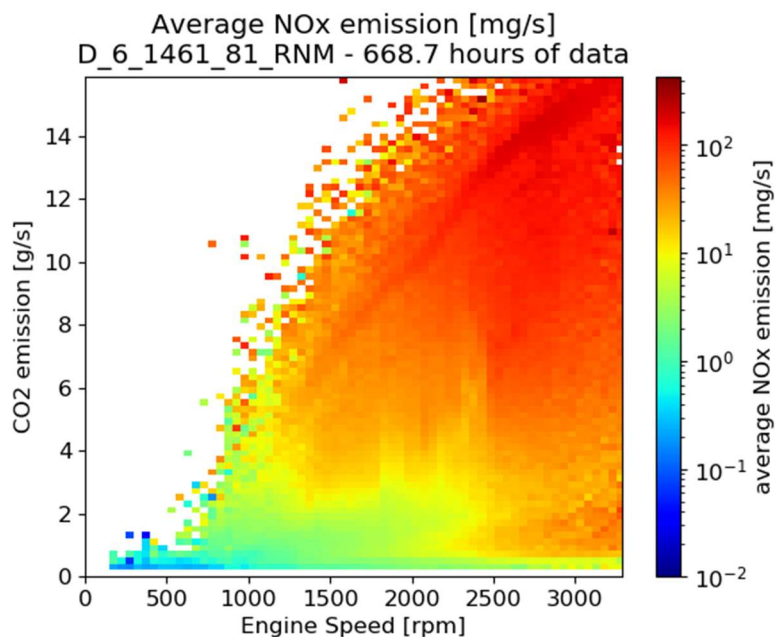


Figure 4.2 Emission map graph of a 1461cc, 81kW Euro 6 Diesel engine with average NO_x emission [mg/s] per engine speed [rpm] and CO₂ [g/s] bin.

Figure 4.3 shows a NO_x emission graph of a Euro 5a diesel engine with almost 330 hours of monitoring data. In the CO₂ emission range higher than 7 grams per second the effect of shifting gears is visible by the dark red lines.

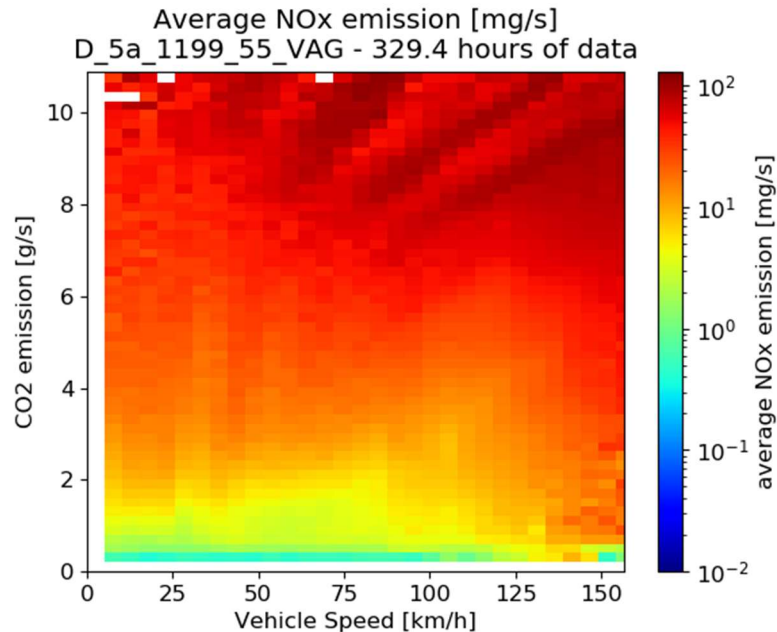


Figure 4.3 Emission map graph of a 1199cc, 55kW Euro 5a Diesel engine with average NO_x emission [mg/s] per speed [km/h] and CO₂ [g/s] bin.

Figure 4.4 shows the emission plot for a Euro 4 petrol engine. In comparison with Figure 4.3 this engine emits less NO_x over the whole spectrum. However the amount of underlying data for Figure 4.4 is much less than Figure 4.3.

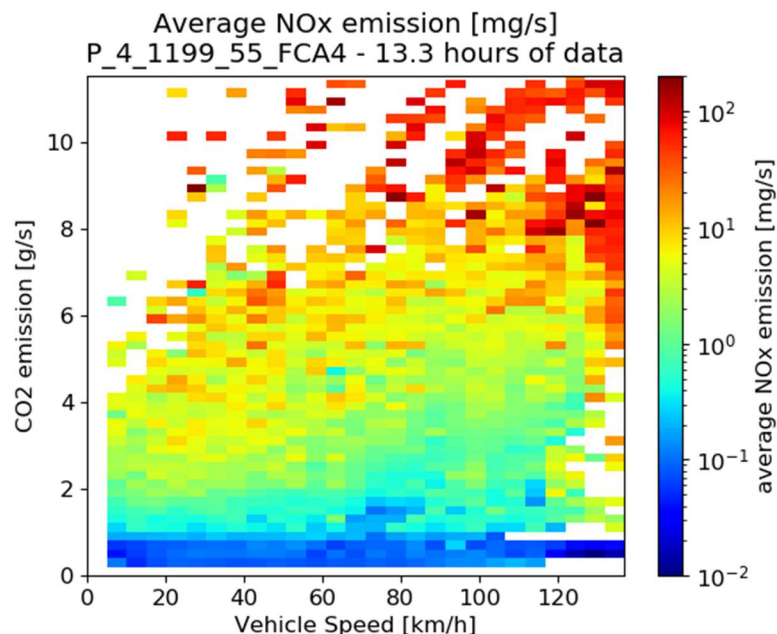


Figure 4.4 Emission map graph of a 1199cc, 55kW Euro 4 petrol engine with average NO_x emissions[mg/s] per speed [km/h] and CO₂[g/s] bin.

These graphs are all complemented by graphs with the datapoint count per bin and, for example, the standard deviation per bin. Figure 4.5 for example shows the datapoint count per bin and Figure 4.6 shows the standard deviation per bin. Figure 4.5 to Figure 4.8 complement the emission graph of Figure 4.1.

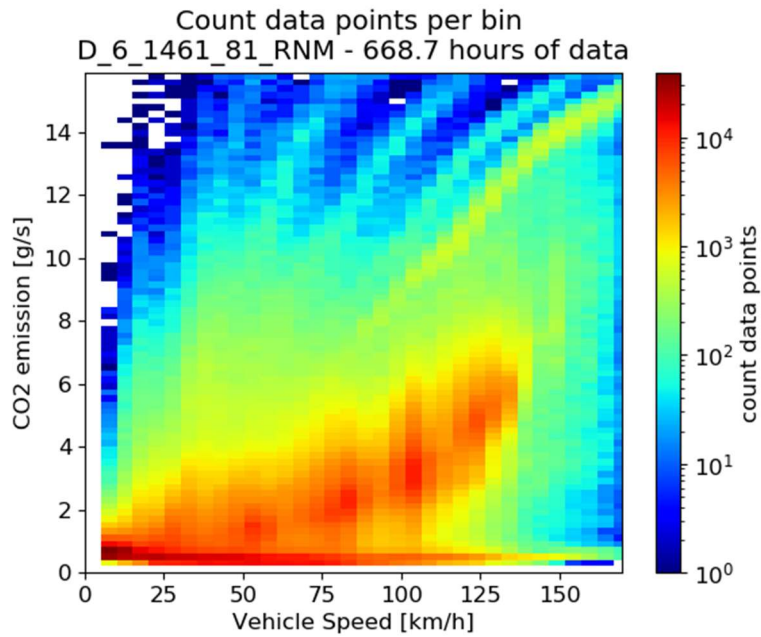


Figure 4.5 Visualisation of the datapoint count per bin of a Euro 6, 1461cc, 81kW diesel engine.

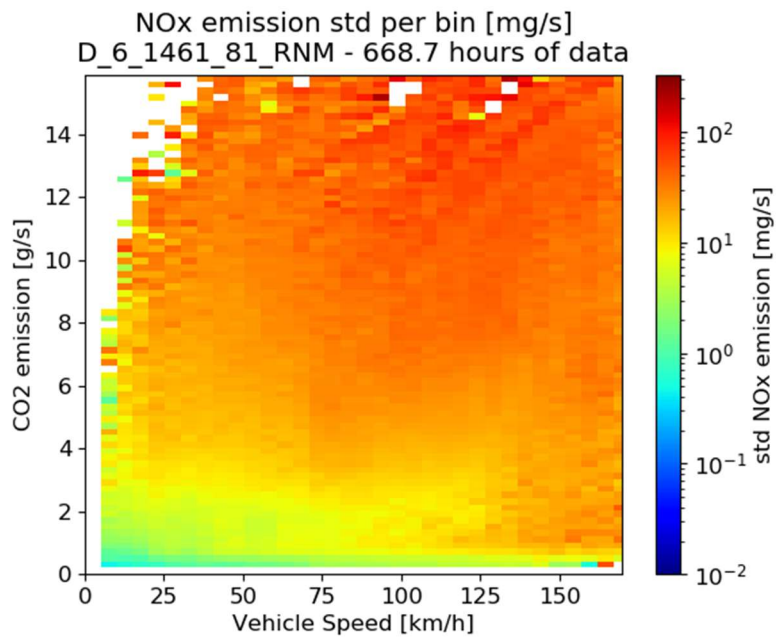


Figure 4.6 Visualisation of the standard deviation of NO_x per bin of a Euro 6, 1461cc, 81kW diesel engine.

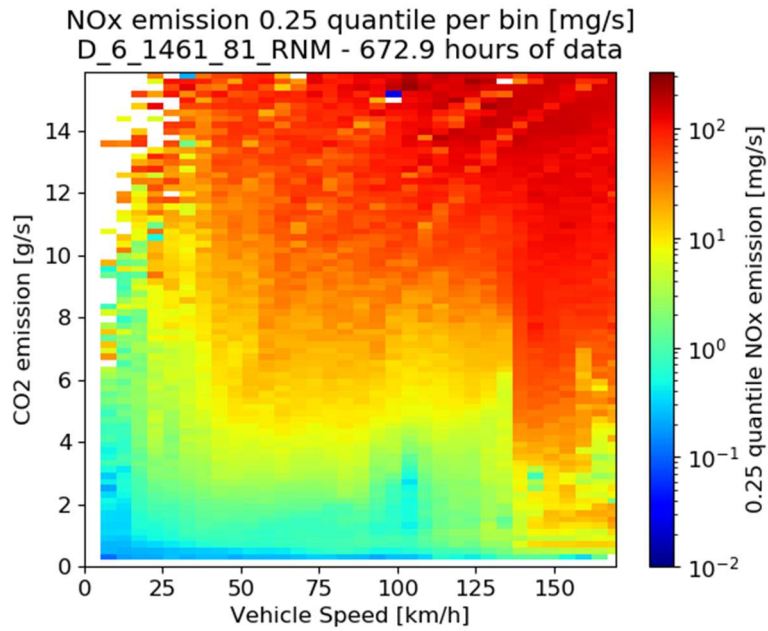


Figure 4.7 Visualisation of the 25th quantile of NOx per bin of a Euro 6, 1461cc, 81 kW diesel engine

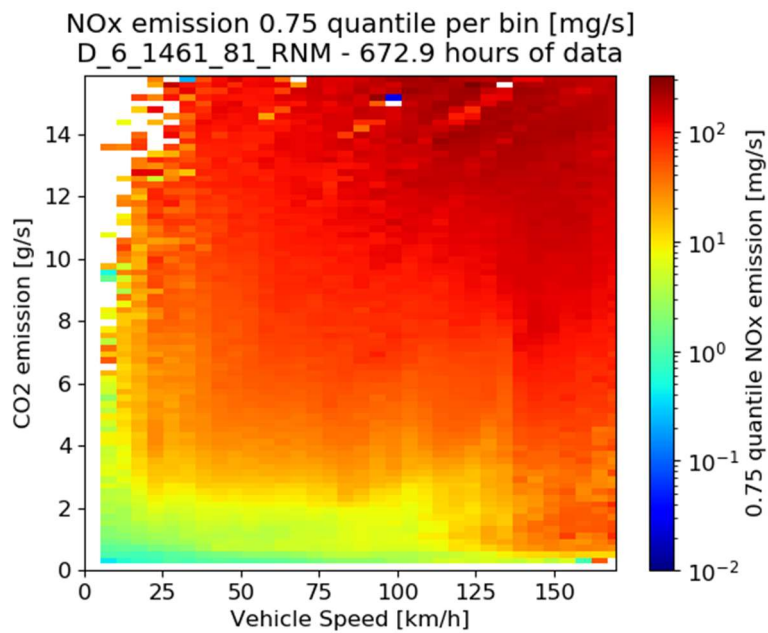


Figure 4.8 Visualisation of the 75th quantile of NOx per bin of a Euro 6, 1461cc, 81 kW diesel engine

5 Data exchange format

A data file structure has been developed to facilitate the exchange of map data among partners, simplify versioning, and enable the implementation of the emission maps in multiple tools.

5.1 Metadata

In order to share data the emission data is standardized. The data exchange format contains all data that is applicable for a specific engine taxonomy code. The standardized emission map has a ".map.txt" extension and is also human readable. As shown in Figure 5.1, the file starts with metadata which contains information about:

- the engine taxonomy code
- total driven kilometres over which the data was gathered
- total time in hours over which the data was gathered
- the number of vehicles which were tested to create the emission map
- the DOI (Digital Object Identifier) reference
- Which emission maps are available in the file. In the figure only one map is mentioned.

```
#####
# START META
#
# ID: D_1461_85_E6
# TOTAL KM: 2730.6
# TOTAL TIME [h]: 46.5
# NUMBER OF VEHICLES: 1
# REFERENCE DOI: tbd
# AVAILABLE MAPS: VEHICLE SPEED - CO2 - NOX - STD NOx - COUNT
# END META
#####
```

Figure 5.1 Screenshot of Metadata

The formal description consists of a syntax description in Backus–Naur form with additional syntactical requirements in text. The root is the <AEM file>, i.e. the file with the ".map.txt" extension.

```
<AEM file> ::= <meta> <map list>
```

The syntax for <meta> is elaborated below, each with a set of requirements.

Formal syntax definition <meta>

```
<meta> ::= "START META" <taxonomy id> <total km> <total time>
        <nr vehicles> <reference doi> <available maps>
        "END META"
<taxonomy id> := "ID:" <taxonomy identifier>
<taxonomy identifier> ::= <identifier>
<total km> ::= "TOTAL KM:" <real number>
<total time> ::= "TOTAL TIME [h]:" <real number>
<real number> ::= <integer> "." <integer>
<nr vehicles> ::= "NUMBER OF VEHICLES:" <integer>
<reference doi> ::= "REFERENCE DOI:" <doi identifier>
<doi identifier> ::= <identifier>
<available maps> ::= "AVAILABLE MAPS:" <map id list>
<map id list> ::= <map id> | <map id> "," <map id list>
```


Requirements <meta>

- The <taxonomy_id> should be formed according to section 2.3 of this document.
- The <doi identifier> should be formed according to ISO 26324 and should refer to (a copy of) this document.
- For each <map id> in the <map id list> there should be a <map> in the <map list> with the same <map id>.
- In an <identifier> only the ASCII characters 33, 34, and 36-126 can be used; an <identifier> should not be equal to a key word.
- The ASCII characters 9 (Horizontal tab), 10 (Line Feed) and 35 (#) are all considered equivalent to a space (ASCII 32) and used to separate key words from <identifier>s, <real number>s, etc.
- In a <real number> there should be no spaces.
- An <integer> is a sequence of digits (ASCII 48-57) without spaces.

5.2 Emission map data

The emission map data follows the metadata. As shown in Figure 5.2, the map starts with the name of the map, followed by notes in which the measurement method can be mentioned. Next the labels are explained. The map in Figure 5.2 consists of:

- vehicle speed[km/h]
- CO2 upper bin limit [g/s]
- average emission within a bin [mg/s]. This could be any pollutant emission.
- standard deviation of the emission within a bin [mg/s]. This could also be followed by the 25th and 75th quartile.
- count of datapoint within a bin [#]

Figure 5.2 and Figure 5.3 show that each map starts and ends with "START" and "END".

```
#####
# START VEHICLE SPEED - CO2 - NOX - STD - COUNT
#
# NOTES: [SEMS monitoring]
# XLABEL: Vehicle Speed upper bin limit [km/h]
# YLABEL: CO2 upper bin limit [g/s]
# Z1LABEL: Avg NOx emissions [mg/s]
# Z2LABEL: Standard deviation NOx emissions [mg/s]
# Z3LABEL: Count per bin [#]
# START DATA VEHICLE SPEED - CO2 - NOX - STD NOX - COUNT
X,Y,Z1,Z2,Z3
5.359042631017666,0.0,0.0,0.0,0.0
5.359042631017666,0.20270030165953629,0.7469680521073303,0.023834804273464114,306.0
5.359042631017666,0.40540060331907257,20.23617307916325,0.07984795620023198,2398.0
5.359042631017666,0.6081009049786088,66.90430484277235,0.1188222323504034,3422.0
```

Figure 5.2 Screenshot of emission map data with START heading, indicating the start of map data

```
144.69415103747698,18.04052684769875,0.0,0.0,0.0
144.69415103747698,18.243027149358266,0.0,0.0,0.0
144.69415103747698,18.445727451017802,0.0,0.0,0.0
# END VEHICLE SPEED - CO2 - NOX - STD NOX - COUNT
```

Figure 5.3 Screenshot of emission map data with END heading, indicating the end of the map data

The syntax for <map list> (which is part of the root <AEM file>) is elaborated below, each with a set of requirements.

Formal syntax definition <map list>

```

<map_list>      ::= <map> | <map> <map_list>
<map>           ::= "START" <map id> <map notes> <map labels>
                  "START DATA" <map id> <csv data> END <map id>
<map id>        ::= <map id list>
<map id list>   ::= <map id text> | <map id text> "-" <map id list>
<map notes>     ::= "NOTES:" "[" <notes text> "]"
<map labels>    ::= "XLABEL:" <label tekst> "YLABEL:" <label tekst>
                  <Zlabel list>
<Zlabel list>  ::= <Zlabel keyword> <label text> |
                  <Zlabel keyword> <label text> <Zlabel list>
<Zlabel keyword> ::= "ZLABEL:" | "Z1LABEL" | "Z2LABEL" | "Z3LABEL" |
                    "Z4LABEL" | "Z5LABEL" | "Z6LABEL" | "Z7LABEL" |
                    "Z8LABEL" | "Z9LABEL"

```

Requirements <map list>

- The three <map id>s in a <map> should be identical.
- A <map id> should contain at least three (3) <map id text>s.
- A <map id text> should not contain a "-" (ASCII 45) and can contain any character allowed in an identifier and spaces.
- A <notes text> should not contain a "]" (ASCII 93) and can contain any character allowed in an identifier and spaces.
- The number of <map id text>s in the <map id> should be identical to the number of <label text>s in the <map labels>.
- All <Zlabel keyword>s in the <Zlabel list> should be different.
For human readability the use of consecutive numbers is recommended.
- The <csv data> should be formatted according to RFC 4180 and the number of columns in the csv data should be identical to the number of <label text>s in the <map labels>.

This makes the exchange format readable for both human and computers. The emission maps will be published on an Open research Data platform (Zenodo) so model developers can use it as input for their models. Qualified parties will be able to update an emission map when there is new and/or additional data for that specific engine taxonomy code available.

6 Conclusions and recommendations

To characterise, store and distribute emission data of vehicles, an emission map concept has been proposed. Experiment-based understanding of the relationship between the use of a vehicle and the emissions are described in a logical and structured way, be it in the form of a map or in the form of a function. Maps or functions can be created on any level of the vehicle taxonomy (D1.1), dependent on distinctiveness and availability of data.

A strict separation of factual data and interpretation has been pursued. Interpolation and smoothing of maps, as well as the implementation of functions, is considered part of the tools that use the maps/functions.

A file exchange format was developed, that can hold meta-information about a vehicle or engine, emission maps and functions. The naming of the files is laid down in this deliverable and is based on an abbreviation of the taxonomy variables.

The emission map concept distinguishes the following layers:

- Tailpipe emissions under hot engine conditions: NO_x, PN, CO, HC
- Tailpipe emissions under cold start conditions: NO_x, PN, CO, HC
- Tailpipe emissions of non-regulated emissions: NO₂, N₂O, PAH, CH₄, cyanides, NH₃
- Wear emissions: particulates from brake wear, tyre wear, road surface wear
- Aging/maintenance: additional tailpipe emissions as a result of aging and/or poor maintenance: NO_x, PN, CO, HC, NO₂, N₂O, PAH, CH₄, cyanides, NH₃
- Tampering: additional tailpipe emissions as a result of tampering: NO_x, PN
- Retrofitting: reduction in tailpipe emissions as a result of retrofitting solutions on older vehicles: NO_x, PN
- Driving dynamics: the impact on tailpipe emissions due to recent driving history: NO_x, NH₃, PN

The dimensions of maps can vary for each layer, dependent on which parameters describe the emission behaviour best. For hot engine tailpipe emissions, vehicle or engine speed, and CO₂ emission mass flow (as a proxy for engine power) were selected. The maps are produced on an engine block level: vehicles sharing the same engine are modelled in the same way.

To handle a varying data availability among vehicle types or engine types, maps have a flexible resolution. The map resolution that is selected, complies to minimum standards in terms of coverage.

The definition of maps and algorithms is work in progress, and new findings from experiments may give insights not yet incorporated in the present description. At this point in the uCARE project, many activities are still ongoing. The following topics need further attention:

- A minimum amount of data per map cell needs to be defined and substantiated;
- Cold start functions need to be completed and tested;
- Non-regulated tailpipe emission maps should be generated depending on availability;
- Experiments on wear emissions have just started. Results will have to be cast into generic functions, and tested; brake wear is not covered yet.
- Experiments on wear emissions have just started. Results will have to be cast into generic functions, and tested; brake wear is not covered yet.
- The effects of maintenance need to be examined and described in a function-like form;
- Maps for retrofitting efficiencies shall be added when test data is available;
- The design of the emission map file needs to be extended to cater for functions;
- The impact of recent driving dynamics on emissions needs to be elucidated.

Note that these topics refer to methodology development. Completing data sets is done during the remainder of the project.

References

- [1] Spreen, J. S. et al. (2016). Assessment of road vehicle emissions: methodology of the Dutch in-service testing programmes - TNO 2016 R11178v2.

- [2] Weilenmann M, Soltic P, Hausberger S. The cold start emissions of light-duty-vehicle fleets: A simplified physics-based model for the estimation of CO₂ and pollutants. *Science of the Total Environment*, 444, 161-176, 2013.

- [3] Pöllhuber H. Simulation der Kaltstartemissionen von Benzin Pkw mit PHEM Advance. Institut für Verbrennungskraftmaschinen und Thermodynamik. Diploma. Graz: Technical University Graz; 2008. Pp. 145.

Annex A

Screenshot of the metadata

```
#####
# START META
#
# ID: D_1461_85_E6
# TOTAL KM: 2730.6
# TOTAL TIME [h]: 46.5
# NUMBER OF VEHICLES: 1
# REFERENCE DOI: tbd
# AVAILABLE MAPS: VEHICLE SPEED - CO2 - NOX - STD NOx - COUNT
# END META
#####
# START VEHICLE SPEED - CO2 - NOX - STD - COUNT
#
# NOTES: [SEMS monitoring]
# XLABEL: Vehicle Speed upper bin limit [km/h]
# YLABEL: CO2 upper bin limit [g/s]
# Z1LABEL: Avg NOx emissions [mg/s]
# Z2LABEL: Standard deviation NOx emissions [mg/s]
# Z3LABEL: Count per bin [#]
# START DATA VEHICLE SPEED - CO2 - NOX - STD NOX - COUNT
X,Y,Z1,Z2,Z3
5.359042631017666,0.0,0.0,0.0,0.0
5.359042631017666,0.20270030165953629,0.7469680521073303,0.023834804273464114,306.0
5.359042631017666,0.40540060331907257,20.23617307916325,0.07984795620023198,2398.0
5.359042631017666,0.6081009049786088,66.90430484277235,0.1188222323504034,3422.0
```

Annex B

Alliances of manufacturers are shown in Table B.1.

Table B.1 Alliances

ALFA	ALFA ROMEO							
BMW	BMW	MINI						
DAIH	DAIHATSU	TOYOTA	CITROEN	PEUGEOT				
FCA	FIAT	ALFA ROMEO	LANCIA	JEEP	CHRYSLER			
FCA2	FIAT	ALFA ROMEO	LANCIA	JEEP	CHRYSLER	SUZUKI		
FCA3	FIAT	FORD	LANCIA					
FCA4	FIAT	ALFA ROMEO	OPEL	CHEVROLET	CADILLAC	SAAB		
FORD	FORD							
GM	OPEL	CHEVROLET						
HYUN	HYUNDAI	KIA						
HYUN2	KIA	MAZDA	HYUNDAI					
MAZD	MAZDA							
MERC	MERCEDES-BENZ							
MERC2	MERCEDES-BENZ INFINITI							
MIT	MITSUBISHI	KIA	HYUNDAI					
MIT2	MITSUBISHI	SMART						
PAG	FORD	VOLVO	JAGUAR LAND R	MAZDA				
PAG2	FORD	VOLVO	JAGUAR LAND R	MAZDA	BMW			
PSA	PEUGEOT	CITROEN	DS					
PSA2	PEUGEOT	CITROEN	DS	OPEL				
PSA3	PEUGEOT	CITROEN	VOLVO					
PSA4	PEUGEOT	CITROEN	DS	MINI				
PSAF	PEUGEOT	CITROEN	FORD	MINI	VOLVO	MAZDA		
RNM	RENAULT	NISSAN	MITSUBISHI	DACIA				
RNM2	RENAULT	NISSAN	MERCEDES	DACIA				
RNM3	RENAULT	NISSAN	DACIA	SMART				
SUZU	SUZUKI							
SUZU2	SUZUKI	NISSAN	OPEL					
TOYO	TOYOTA	PEUGEOT	CITROEN					
TOYO2	TOYOTA	DAIHATSU	LEXUS	SUBARU				
TRIT	CHRYSLER	MINI						
VAG	VOLKSWAGEN	AUDI	SEAT	SKODA				
VAG2	VOLKSWAGEN	AUDI	SEAT	SKODA	JEEP	DODGE	MITSUBISHI	
VOLV	VOLVO							

The association of alliance codes and particular engines is work in progress.

Annex C

Incorporating the effect of dynamics in NO_x emission maps

Introduction

On top of the generated emission maps, a proposal is made to describe the influence of dynamic behaviour on the NO_x emissions of passenger cars. As a case example of implementation of the emission maps, this influence is formulated based on the emission map as a function of vehicle speed and CO₂ mass flow. The implementation will be further elaborated by means of an example from existing measurement data.

Effect of vehicle dynamics on variation in NO_x emission

The vehicle dynamics can be formulated utilizing the CO₂ emission flowrate. The CO₂ emission is a proxy of the engine load, therefore variation of the CO₂ emission rate can be used to describe the variation of engine load that is usually correlated to the vehicle dynamics.

The variation of the CO₂ emission is defined as the difference between the CO₂ emission flowrate and the moving average of the CO₂ emission.

The variation of the NO_x emission is defined as the residuals between the measured NO_x and the average NO_x emission from the augmented emission map as a function of vehicle speed and CO₂ emission. Determination of the window size used to calculate the moving average of CO₂ is based on the autocorrelation of the NO_x residual.

The effect of the variation of the CO₂ emission towards the NO_x variation is defined as the gradient of the linear regression of the NO_x residuals and squared CO₂ variation in each bin of the generated average NO_x emission map:

$$CO_{2,variation} = CO_{2,measurement} - CO_{2,rolling\ mean}$$

$$\left. \frac{NO_{x,residual}}{(CO_{2,variation})^2} \right|_{@(vehic\ speed,CO_2)bin}$$

An example test case is used to illustrate the formulation step by step.

Example test case: Volkswagen Caddy

Referring to the generated NO_x emission map as a function of vehicle speed and CO mass flow of the Volkswagen Caddy 2018 in Figure 3.1, the calculation of NO_x residuals is shown in Figure C.0.1 and the autocorrelation of NO_x residuals is shown in Figure C.0.2.

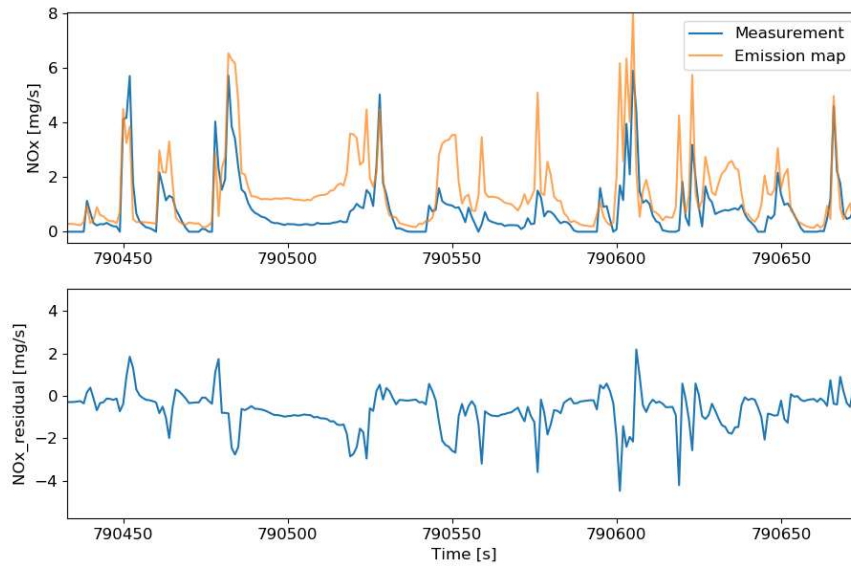


Figure C.0.1 Comparison of NO_x emissions from measurement data and augmented emission map as a function of vehicle speed and CO₂ emission

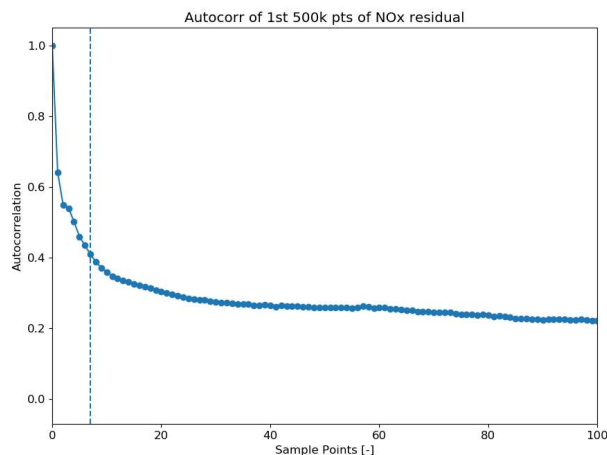


Figure C.0.2 Autocorrelation of residual NO_x. The vertical line shows the sample point where the autocorrelation value reaches 0.4

The duration of the moving average window of CO₂ values is selected at the point that the autocorrelation value reaches 0.4. In this example, the vertical line indicates that the window size is 7 seconds.

Once the moving average of the measured CO₂ is calculated, the NO_x residuals and the squared CO₂ variation are binned by vehicle speed and CO₂ mass flow, similar to the way the emission maps are designed. The gradient of the linear regression of the NO_x residuals and squared CO₂ variation is then calculated and plotted, as visualized in Figure C.0.3.

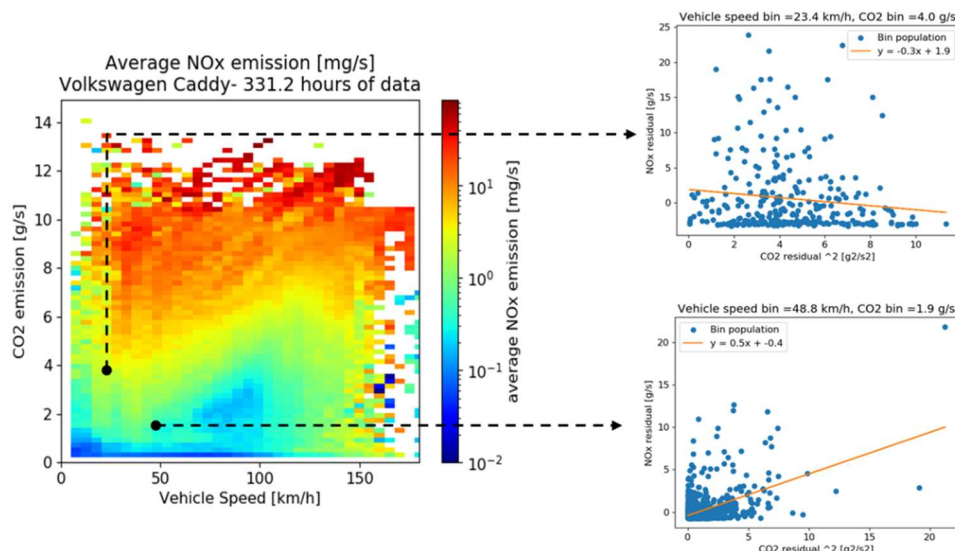


Figure C.0.3 Calculation of the effect of dynamics on NO_x variation, visualized in the emission map. The small windows visualize the calculation of the gradient of the linear regression of the NO_x residual as function of squared CO₂ variation.

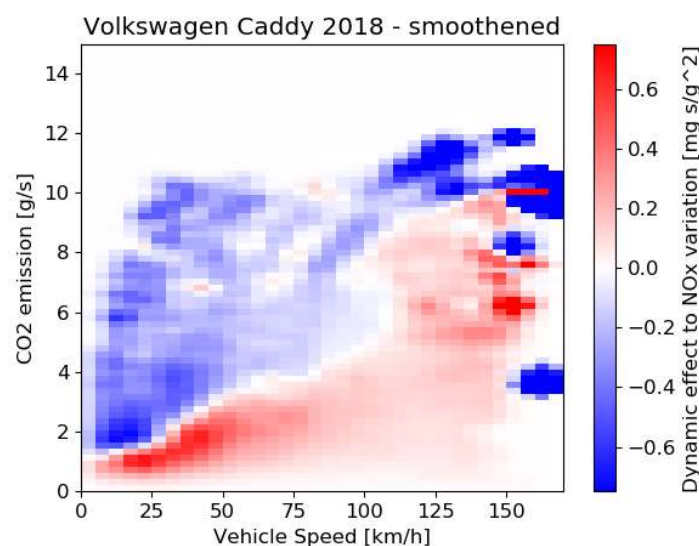


Figure C.0.4 Effect of vehicle dynamics on NO_x variation (emission map design)

The resulting gradients are then plotted similarly as the emission map and smoothed to show consistent trend, as shown in Figure C.0.4.

The red area shows the driving profile that is associated with constant speed driving. For example, driving at a constant speed of 50 km/h will have an average CO₂ emission of around 2 g/s. Introducing dynamic driving in this area will result in NO_x emission variation up to 0.5 mg/s per squared CO₂ variance.

The blue area is associated with acceleration, during which the engine load temporarily increases. The NO_x emission in the blue area is already high as it represents the acceleration period during driving rather than constant speed driving. Any change in dynamics in this area (for example, more constant speed driving) would result in a negative NO_x variation from the already high NO_x average.

While Figure C.0.4 adequately visualizes the effect of vehicle dynamics on NO_x emission variation, the validation of this effect for NO_x emission prediction is still ongoing. Specifically, whether the result from Figure C.0.4 can be used along with the base emission map Figure C.0.3 for a more accurate NO_x emission prediction.

Annex D

Cold start tailpipe emissions modelling

Model description [2]:

The input data required by the model consist of ambient temperature (T_{amb}), vehicle mass (mass) and drag coefficients (f_0, f_1, f_2), and the information regarding the driving profile, including velocity (v) and engine speed (n).

The model is based on a set of 13 parameters ($w_p, w_n, w_0, Q_{in0}, n_0, q_1, q_2, t_{1_X}, t_{2_X}, t_{3_X}, m_{1_X}, m_{2_X}, m_{3_X}$ with $X = CO, HC, NO_x$ and PN) for each individual vehicle, which are determined using specific chassis dynamometer measurements. So far only measurements of the IUFC cycle at two or more ambient temperatures have been used to parametrize the model, but the possibility of using data from other cycles (e.g. WLTP) or from PEMS measurements is being evaluated.

The model consists of six different sections:

1) Cool down of vehicle during parking

In a first step the initial temperature of the after-treatment system (T_{a0}) and the engine (T_{e0}) are estimated using cool down curves that were derived from 15 cool down tests with 4 different vehicles [3]. In case of longer stop times ($>6h$) T_{a0} and T_{e0} are set equal to the ambient temperature.

2) Model for vehicles motion:

The wheel power (P) is calculated from the vehicle and driving parameters as follows:

$$P = v * F_{wheel} = v * (F_{acc} + F_{drag}) = v * (mass * \frac{dv}{dt} + f_0 + f_1 * v + f_2 * v^2)$$

3) Engine model for hot running conditions:

The input power during hot running conditions (Q_{in_hot}) is calculated as a linear function of the mechanical power (P) and the engine speed (n):

$$Q_{in_hot} = w_p * P + w_n * n + w_0$$

Q_{in_hot} is corrected for motoring and idle conditions as follows:

$$Q_{in_hot_motoring} = 0.9 * Q_{in0} * \frac{n}{n_0}$$

$$Q_{in_hot_idle} = Q_{in} * \frac{n}{n_0}$$

The heating power (Q_{h_hot}) is then calculated as the difference between the input power and the power delivered to the wheels:

$$Q_{h_hot} = Q_{in_hot} - P$$

A portion of this heat is transferred to the coolant, while the rest leaves the engine with the exhaust gas.

4) Engine model for cold start

During the cold start, the input power to the engine is higher than in hot running conditions ($\Delta Q_{in} = Q_{in_cold} - Q_{in_hot} > 0$), primarily to overcome the increased friction of the cold engine, or else as a result of a controller decision to have a faster warm-up. Because it is not possible to measure the temperature at all friction points within the engine, we assume that the relevant temperature for the engine friction (T_{frict}) evolves similarly to the coolant

temperature. Thus, during the cold start (when the cooling circuit is closed), T_{frict} is considered to rise linearly with the heating energy:

$$T_{frict} = T_{e0} + q_2 * \int_0^t Q_{h_hot} * dt$$

where T_{e0} is the engine temperature at the engine start.

The cold start extra input power (ΔQ_{in}) is assumed to be proportional to the input power and to follow a second order law over temperature (determined based on correlation with measurement data):

$$\Delta Q_{in} = Q_{in_hot} * (q_1 * (T_{e_hot} - T_{frict}))^2 = Q_{in_hot} * (q_1 * (T_{e_hot} - T_{e0} - q_2 * \int_0^t Q_{h_hot} * dt))^2$$

ΔQ_{in} becomes zero when T_{frict} reaches the hot running engine temperature (T_{ehot}).

From this we derive the total heating power during a cold start (Q_{h_cold} , in the following denoted as Q_h):

$$Q_{h_cold} = Q_{h_hot} + \Delta Q_{in}$$

5) Model for the cold start duration:

For a given pollutant X (X=CO, HC, NO_x or PN), the heating power over the cold start period is estimated as

$$Q_X = t_{1_X} * (T_{e_hot} - T_{a0}) + t_{2_X} * (e^{t_{3_X} * (T_{e_ho} - T_{a0})} - 1)$$

The end of the cold start (t_{end_X}) is then determined by minimizing the difference between the cumulated heating power and the cold start heating power for the pollutant X:

$$t_{end_X} : \text{Min of } Q_{diff} = \int_0^{t_{end_X}} Q_h * dt - Q_X$$

6) Pollutants model:

For a given pollutant X, the cold start extra emissions (dmX) are estimated as:

$$dmX = m_{ex} * (m_{1_X} - m_{2_X} * T_{e0})^3 * e^{-m_{3_X} * (\int_0^t Q_h)^{1/2}}$$

where m_{exh} is the exhaust mass flow, which, if not available from measurements, can be estimated using:

$$m_{exh} = \frac{Q_{in}}{2538.7}$$

The factor in the denominator takes into account the heat capacity of the exhaust gas and the percentage of the heat power that flows into the exhaust system.

As mentioned above, the model parameters are determined for each vehicle using specific chassis dynamometer measurements. If the test data to parametrize the cold start model for single engine families is not available or is insufficient, the model parameters might be aggregated at a Euro-class/fuel-level.

The model parameters will be included in the map files and used in WP2 for the calculation of the cold start extra emissions. Some variables in this model (such as wheel power or heating power) are available directly from the PHEMS model (WP2). If such variables were to be taken from the PHEMS model (validation required), this would lead to a decrease in the number of required model parameters. It is important to note that the model for the cold start extra emissions is still under development and changes may occur during the implementation of the model into the PHEM model.