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Executive summary

This deliverable provides preliminary insight in how a ranking of pollutant reduction potentials for different uCARe measures could look like. Based on the modelling work performed in uCARe's work package 2, a framework is proposed for characterising emission reductions that are to be derived from the real-world implementation of pilot projects in work package 3. Such data has not yet been gathered, indicating that this deliverable is a working document that will be updated as soon as this situation changes and a significant amount of measurements can be discussed.

However, by applying existing real-driving emissions (RDE) data from earlier test campaigns obtained using portable emissions measurement systems (PEMS) in the uCARe model, potential emission reductions can be estimated. This can be done by comparing the trips as they were originally driven to a simulated 'super eco' mode, based on the same input variables but with optimised speeds and gear selection. A first validation exercise indicates that, depending on the original trip dynamics, NOx reductions can range from a few percent up to 70%. This indicates the extent to which everyday drivers and their driving behaviour are a largely unexploited domain of reducing pollutant emissions for the existing vehicle fleet.

Next to that, a literature review is presented in which we discuss the most important measures that can be taken to reduce our impact on the environment when driving road vehicles. Whereas earlier studies typically look at energy efficiencies and fuel economy (hence CO_2 emissions), pollutant emissions are only rarely taken into scope. As such, uCARe will fill in a substantial gap in general knowledge on eco-driving. Compared to the commonly known way of eco-driving, focussing on CO_2, a focus on pollutants largely includes the same parameters. As such, driving dynamics (accelerating, decelerating), driving speed, idling time and route selection are decisive, whereas the set-up of a vehicle is important as well. First results from WP2 modelling indicate that tyre inflation and use of winter tyres can have a substantial impact on NOx emissions. Also, specific attention should be placed on avoiding external attachments to the bodyworks of vehicles (such as roof boxes) as these diminish aerodynamic performance.

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Definitions & Abbreviations

A/C	Air conditioning
Beta	Share of drivers implementing uCARe measures in everyday driving
CO	Carbon monoxide
CO_2	Carbon dioxide
CSEE	Cold start extra emissions
Cw	Aerodynamic drag coefficient
DoW	Description of work
DeltaEF	Potential emission reduction
EGR	Exhaust gas recirculation
ER	Emission reduction
FeDS	Full ecoDriver system
Fr_0	Tyre rolling resistance
Gamma	Likeliness of drivers implementing uCARe measures on average
HBEFA	Handbook of Emission Factors
HC	Hydrocarbons
HDV	Heavy-duty vehicle
HMI	Human-machine interface
ICE	Internal combustion engine
LCV	Light-commercial vehicle
NOx	Nitrogen oxides
OBD	Onboard diagnostics
OEM	Original equipment manufacturer
PEMS	Portable emissions measurement system
PHEM	Passenger Car and Heavy-Duty Emission Model
PM	Particulate matter
PN	Particle number
RDE	Real-driving emissions
RPA	Relative positive acceleration
SCR	Selective catalytic reduction system
SEMS	Smart emissions measurement system
TUG	Technical University Graz
TWC	Three-way catalyst
WLTP	Worldwide Light-vehicles 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 from given traffic activity, 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 the effectiveness of emission legislation (or the limits thereof; e.g. 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. uCARe enables an essential next step providing user targeted emission reduction measures. These measures will be implemented and evaluated in real-life pilot projects.

The overall 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 is the first deliverable resulting from the work performed in work package (WP) 4. As such, this deliverable will present a ranking in terms of the pollutant emission reduction potentials yielded from the different uCARe measures aiming for a change in driver behaviour as they are applied throughout the pilot projects in WP3. This emission reduction potential is determined by both the so-called ‘gamma’ factor, or the rate of effectiveness of the measures in targeted traffic situations, and the ‘beta’ factor representing the likeliness of drivers implementing uCARe measures in daily life. In deliverable 4.2, this likeliness will be investigated through surveys and interviews, to complement the insights from this deliverable. Thus, the ranking presented in this deliverable will be updated to a final list of the most effective ways for vehicle users to reduce their impact on the environment whilst driving. This input is required in task 4.3 to model uCARe’s impact on entire vehicle fleets if a large-scale roll-out would be targeted, hence moving beyond the pilot projects.

A delayed roll-out of pilots following the restrictions imposed by the CoViD-19 pandemic forces us to deviate from the original plan as no field experiment data is available yet. Therefore, we will first look at the potential emission reductions following the first simulation work performed in WP2, while consulting the available literature for insights on reductions following changes in a consumer’s driving style and driving behaviour. These insights can be related to the earlier mentioned gamma and beta factors. The ranking presented in this deliverable will thus serve as a basis for a revision in task 4.2 within this work package, while it will also be revised as soon as the first pilot data comes in from WP3.

2 Purpose of the document

2.1 Document Structure

Table 2-1 Overview of the document structure

Chapter	Purpose of the document
Chapter 1	Background of the uCARe project
Chapter 2	Purpose of the document
Chapter 3	An introduction to eco-driving Purpose: A literature review on eco-driving, how it is generally conceived, and which aspects are most important to influence emissions.
Chapter 4	Quantification of emission reduction potential Purpose: An overview of how emission reduction potentials can be measured or determined, what benefits/disadvantages the different methods represent, and accurate they are.
Chapter 5	The ecoDriver project (2016) Purpose: A short review of a previous European project for which a lot of similarities can be found, although the latter mainly focussed on energy efficiency.
Chapter 6	uCARe measures and their reduction potential Purpose: A preliminary insight in which potentials can be determined from the simulation works in WP2
Chapter 7	Conclusions and recommendations

2.2 Deviations from original Description of Work (DoW)

2.2.1 Description of work related to deliverable as given in DoW

In a first step, we quantify the emission reduction effect for each of the measures and interventions tested in the pilot projects of WP3. For this, we will closely co-operate with our colleagues from WP3, ensuring that the results of the pilot studies are accurately reflected in our quantitative assessment. We will assess user behaviour before and after the implementation of the measure, for example using in-vehicle monitoring systems or repair/maintenance/replacement records. Our assessment will extend to cover longer-term effects that can be measured during the duration of the project. In addition, we will also quantify the emission reduction effect of measures and interventions not tested as part of the pilot projects based on data obtained from the literature, albeit in less detail.

At the end of Task 4.1, we will have developed a preliminary ranking of the various consumer behaviour measures and interventions, listing them in the order of how effective they are in reducing emissions on a per vehicle basis. This will allow for a comparison of the different measures and interventions. For example, we would expect to get a first indication on whether the purchase decision for a type of vehicle or measures at a later point in time during the lifetime of the vehicle tends to have a larger effect on emissions.

The following sub-tasks 4.2-4.4 will then add information on how effective each of the measures and interventions is likely to be if rolled out more broadly.

2.2.2 Time deviations from original DoW

None

2.2.3 Content deviations from original DoW

This deliverable presents the interim description of the emission reduction potential following intervention strategies tested in uCARe WP3 ‘Pilot projects with stakeholders’. In that sense, there are no deviations from the DoW. However, the foreseen available material from pilots has not yet been delivered.

Therefore, this deliverable will serve as an intermediate working document that will follow the proceedings in WP3 and will be updated as soon as measurement data comes in for post-processing.

3 An introduction to eco-driving

Significant passenger car, light-commercial vehicle (LCV) and heavy-duty vehicle (HDV) emission reductions have been achieved over the last decades. Driving forces behind these accomplishments are various. First there are emission standards, known in Europe as the 'Euro' classes[1], which have led to technological improvements of emission reduction systems. Then, there are innovations in engine technologies (e.g. downsizing) and powertrain optimisations, e.g. through hybridisation and electrification. Also, conventional fuels have improved while synthetic fuels are in a far stage of development, incrementally bringing down the need for fossil fuels whilst improving the characteristics of these newer fuels compared to fossil fuels like petrol and diesel. Whereas substantial R&D budgets have been spent to realise these innovations, the projected gains are only marginal for further reductions of both fuel consumption (and thus carbon dioxide (CO_2) emissions) and pollutant emissions. As such, Zhou et al estimated the achieved conventional powertrain efficiency gains to be in the 4% – 10% range [1], while further improvements will likely make conventional powertrains less competitive to zero-emission technology that is on the brink of a large-scale breakthrough, spurred by dwindling production costs and increased consumer interest as more vehicle models are introduced [2],[3]. Despite this, conventional vehicles with engines running on fossil fuels will likely remain the focus of the industry and this at least for the coming decade. At least, as several countries have already put a final date on the sales of fossil-fuelled passenger cars[2], starting from as early as 2025 (Norway).

One other aspect of achieving further emission reductions for the existing fleet is the impact of the driving style and 'eco-driving'. Although 'eco-driving' has been around for more than a decade when it comes to reducing CO_2 emissions and fuel consumption (Keyvangar et al., 2018), this is still a largely uncharted domain when it comes to reducing hazardous emissions. Dedicated education programs aimed at everyday drivers are more cost-effective than retrofitting entire existing fleets with emission reduction systems. The same is true when we compare the potential reductions from eco-driving with substantial investments in road infrastructure, that would have the same objective of bringing down vehicle speeds and smoothening traffic flows (Rodriguez et al., 2016). For instance, fuel efficiency improvements related to eco-driving are estimated to amount up to 45% Xu et al. (2017).

However, the link between driving style and CO_2 is more straightforward and easier to grasp for the common vehicle users than its link to NOx. A reduction of CO_2 reduces fuel consumption which means a direct economic benefit to the driver. Although the link between CO_2 and climate change is a more complex topic and generally not easily understood, this situation is far worse for pollutants like particulate matter (PM) and nitrogen oxides (NOx).

Since the introduction of the diesel particulate filter (DPF) with Euro 5b emission legislation in 2011, an end came to visible diesel exhaust plumes as soot particles are trapped and oxidised at extremely high efficiencies, largely exceeding 95% [7], [8]. This largely makes particulate emissions, both in terms of particle mass (PM) and number (PN), an issue of the past when a DPF functions optimally. However, driving style will barely have an influence on PM emissions, although this cannot be said from PN emissions as they are sensitive to cold starts. This situation nonetheless changes completely when the DPF substrate is worn out and/or damaged, or, in the worst case, illegally removed. As such, PM emissions may increase by a factor 100 – 200, while PN emissions may increase by a factor 1,000 – 10,000 [9].

[1] See e.g. https://dieselnet.com/standards/eu/ld.php

[2] See e.g. https://carpart.com.au/blog/car-part-world-news/14-countries-banning-fossil-fuel-vehicles-norway-leads-in-2025

NOx reduction systems such as selective catalytic reduction system (SCR) also have a high-efficiency potential although their practical effectiveness largely depends on how the system is calibrated for real-world operation. This became clear in the wake of the 2015 diesel scandal, as illegal de-coupling of NOx emission reduction systems outside of the official type-approval test conditions came to light for diesel passenger cars. More stringent emission legislation, including on-road tests with portable emissions measurement systems (PEMS) during type-approval (as of Euro 6d-Temp), together with in-service conformity testing for vehicles during their first 5 years or 100,000 km from Euro 6d onwards are expected to close this gap and to make sure car manufacturers calibrate their emission control systems for a realistic engine operation range. Third party testing by independent institutions will subsequently make sure that new vehicles will be tested at the boundaries of the test requirements to counter type-approval tests with more realistic driving situations. uCARe focusses on the existing fleet, rather than on new models that are better regulated. The focus is on the earlier (mainly Euro 5 and 6b,c,d-Temp) technologies for which the SCR systems are proven to be less effective in reality. As such, NOx emissions from the existing diesel car fleet cannot be de-coupled from driving behaviour as the SCR and complementary exhaust gas recirculation (EGR) systems do not cover the entire engine operating range during the full spectrum of vehicle use. The most pronounced example is driving in an urban context, characterised by low exhaust gas temperatures due to low speeds and frequent start-stop traffic. This does not allow the typical light-off temperature for an SCR to work optimally, leading to high urban NOx emissions.

3.1 The driver’s potential in reducing pollutant emissions

As stated by Huang et al., the driver is an often-overlooked factor in determining vehicle performance, with eco-driving being a low-cost means to significantly bring down fuel consumption and pollutant emissions [10]. Eco-driving is often trained to vehicle users in dedicated programs but can also be taught to starters through driving schools (e.g. [11], [12]).

Sivak and Schoettle define eco-driving following two important phases, being vehicle purchase and the post-purchase decisions [4]. These decisions are categorised as

- Strategic (vehicle selection & maintenance)
- Tactical (route planning and vehicle loading (weight))
- Operational (driving style)

Within uCARe, this categorisation is mainly followed, albeit that the emphasis is put on driving style and how driver behaviour in traffic can be altered. If one would rank the beforementioned decisions, the vehicle selection proves to be of chief importance if lifetime emissions are considered. As such, one may expect that choosing a fuel-efficient vehicle, for instance a hybrid vehicle combining an internal combustion engine (ICE) with an electrified powertrain, will have the largest impact on reducing both lifetime CO_2 and pollutant emissions. The reasoning behind this is simple as reducing absolute emissions will likely bring down pollutant levels per kilometre driven. Fuel selection at the point of purchasing a new vehicle is important too, as opting for a petrol vehicle rather than a diesel variant can have far-reaching results if NOx and PM emissions are concerned. For the latter case, however, non-exhaust PM emissions should not be overlooked as they are relatively technology-neutral. Non-exhaust PM may originate from tyre and brake wear, as well as road wear. As such, a petrol car will typically emit similar levels of non-exhaust PM as a diesel variant, which will more or less be same as for a battery-electric vehicle (BEV) given that the latter’s increased tyre wear will be compensated by a reduced brake wear due to regenerative braking on the electric motor [13]. For conventional vehicles that generally do not make use of regenerative braking systems, driving style can be an important determinant for non-exhaust PM emissions. Post-purchase decisions, on the other hand, can lead to reductions in fuel consumption up to 45% [4].

Barkenbus (2010) broadened the scope of eco-driving, complementing the usual suspects (driving behaviour, trip planning, load management, fuelling and maintenance) with public education, driving feedback devices, regulation, fiscal incentives and social norm reinforcement [14]. Huang et al. narrow down the focus to the specific influence the driver can exert on fuel consumption and pollutant emissions, given that these factors are easiest to implement by everyday drivers without the need of buying another car [15]. These factors will be discussed in the following sections.

3.1.1 Driving speed

The first factor is the **driving speed**, for which a rule of thumb is to keep a constant speed in various road conditions. This aspect is typically linked to fuel consumption only, although constant speeds result in stable pollutant conversions as well. If one would plot instantaneous emissions of pollutants like NOx during an on-road measurement campaign using PEMS, spikes would mainly be seen during so-called ‘transient’ operation points. These are often brief moments during which the operation of an engine alters, for instance when a speed limit increases, leading to momentarily changes in combustion chamber mixtures and the consequential composition of exhaust gases and their temperature. Whereas emission control systems like the SCR for diesel and a three-way catalyst (TWC) for petrol vehicles perform at their peak efficiency during steady, hot exhaust gas compositions, spikes in emissions occur in between two steady working points. These spikes may largely determine the averaged emission factor following an emission test using portable emissions measurement systems (PEMS) or smart emission measurement systems (SEMS), especially when pollutant emissions are low in general. Ideal cruising speeds for conventional cars in terms of optimal fuel consumption and pollutant emissions were found in the range of 60 – 90 km/h, as stated by El Shawarby et al.[16], while for buses this optimal point should be between 50 – 70 km/h [17]. For petrol cars specifically, this is found to be slightly different, with optimal speeds between 60 – 80 km/h, while for optimal motor efficiencies for electric vehicles we look at the 50 – 60 km/h range[18]. These speeds are typically below the maximum speeds allowed on European motorways, i.e. around 120 – 130 km/h. In that viewpoint, it makes sense to bring down maximum speeds in these conditions, as this is currently being done in the Netherlands. Concerning fuel consumption, a reduction of the maximum speed from 120 to 110 km/h would lead to 12% more efficient diesel cars and 18% more efficient petrol cars, while benefits are also to be expected for both petrol and diesel NOx and PM emissions [19]. Recent insights from a Flemish remote sensing campaign brought to light that for some petrol cars, motorway driving leads to high NOx emissions, whereas in general they were assumed to be low-emitters overall (Hooftman et al., 2020). This indicates how real-driving emission (RDE) legislation applied during on-road type-approval tests currently fail to properly represent high engine load operation for passenger cars, something that is also true for low engine loads during city driving for heavy-duty vehicles (HDV).

In real-world traffic, however, optimal speeds can only seldomly be maintained due to various factors like speed limits, traffic flow, road grades, etc. Therefore, as a rule of thumb, approaching and/or maintaining the speed limit is advised as a proxy.

3.1.2 Driving dynamics

A second factor consists of the **driving dynamics**, characterised by accelerating and decelerating. Here, a linking factor with the optimal speed discussed earlier is that cruising speeds are to be maintained as close as possible. Avoiding harsh accelerations and braking is a commonly well-understood way of practicing eco-driving. Nonetheless, the configuration of the road and the traffic density can be determining factors for a given driving style too[20]. Also, there seems to be no consensus in literature on how optimal speeds are to be reached; either by reaching this speed as swiftly as possible or by avoiding steep accelerations overall. All-in-all, the context will be determining the impact of how a vehicle is accelerated, as stop-go traffic in urban situations will be a key cause for high pollutant emissions, including carbon monoxide (CO), hydrocarbons (HC) and NOx. Gallus et al. (2017) characterised the aggressiveness of real-world driving styles based on the relative positive acceleration (RPA) following PEMS tests and found that aggressive driving increased NOx emissions by 50% – 220%, while for CO and HC no significant differences were reported compared to a normal driving style [21]. This can be explained by the prevalence of HC and CO emissions occurring mainly when (petrol) exhaust gases are cold and/or accelerations occur in an open-loop mode with emission control briefly working in a sub-optimal way. For diesel engines, HC and CO emissions are typically very low, regardless of how the vehicle is driven. This is mainly due to the implementation of an oxidation catalyst shortly after the engine. Rodriguez et al. performed on-road PEMS tests on 78 light-duty petrol and CNG vehicles and concluded that large reductions would be possible if traffic flows and driving styles would be smoothened [5]. As such, pollutant emissions in an urban context could drop by 13% for CO and HC, while NOx could be reduced by 24%. They considered that education of drivers is a far more cost-effective way of reducing traffic emissions than investing heavily in infrastructural changes. Also, they recommend prioritising eco-driving education for drivers of the most polluting vehicles, as this would yield the largest absolute emission reductions.

3.1.3 Gear selection

Concerning the **gear shifting pattern**, an optimal use consists of low engine speeds and moderate throttling, and this for both petrol and diesel cars [22]. This finding, however, focuses on CO_2 emissions. For Euro 5 diesel cars, typically not equipped with an SCR system, this would indeed lead to lower fuel consumption and thus lower CO_2 emissions, but would increase NOx emissions. Also, for SCR-equipped diesel cars and vans, driving in this way will likely lead to high NOx emissions as the SCR will not reach it's desired catalyst light-off temperature. This fact characterises that the same recommendations for CO_2 related eco-driving do not always hold for pollutant emissions. Another such example is that the desired speed should be reached as smoothly as possible while shifting to higher gears early. For decelerating, it is advised to make use of the braking capacity of the engine in the highest possible gear engaged. Whereas these driver recommendations are not discussed in terms of pollutant emissions in literature, uCARe insights will broaden the scope.

3.1.4 Idling

Next, **idling** the engine is recommended to be minimised whenever possible. Although most studies discussing idling refer to heavy-duty engines, large similarities exist for light-duty variants. As such, fuel combustion is found to be incomplete during idling due to insufficient engine temperatures [23]. This has adverse effects on both pollutant emissions (given that unburned fuel molecules are emitted by the engine) and engine wear. The latter occurs as engine oils diluted by unburned fuel and soot particles, reducing the lubricant efficiencies [24]. Next, huge volumes of fuel are wasted during idling if entire fleets are taken into scope, as engines running without delivering useful power work at a zero-fuel efficiency. Therefore, prevention of idling for those older vehicle models that have no automatic start-stop function built in, turning off the engine when it's not required to run, can result in substantial pollutant savings. Such start-stop functions can improve fuel efficiency by 20% (if they are not disactivated by the driver). Education campaigns may be key for reaching this goal, as during the colder months, vehicle owners still tend to pre-heat their passenger cabins by idling the engine. As emission control systems often need to heat up to become efficient, it becomes clear what impact idling with a cold engine can have. This effect will be quantified in uCARe and will be incorporated in this document in Spring 2021. As a rule of thumb, it is suggested to turn off the engine if the vehicle is not expected to continue moving within one minute. Also, idling can be significantly reduced when upcoming traffic is anticipated, keeping smooth cruising speeds and avoiding harsh changes in motion. As such, potentially dangerous situations are avoided during which a driver would intentionally turn off the engine in traffic. A study by Mandava et al. indicated that a dynamic speed advice for drivers that focused on reducing idling times yielded 12% - 14% lower pollutant emissions [25]. In an education campaign by Rutty et al., relying on pre- and post-training training and feedback to drivers, average idling times reduced by 4-10% [12].

3.1.5 Routing

Route choices are found to have an important impact on pollutant emissions as well. For a given destination, GPS systems typically provide in several ways to get there (e.g. fast, short and 'eco'). The fast option will likely refer to a motorway trip but may include extra kilometres to reach that motorway. The short option may include congested traffic leading to an increase in start-stop traffic, which is in turn adverse for both CO_2 and pollutant emissions. A trade-off is therefore needed for which more optimal driving speeds can be maintained, while compromising between travel time and distance. Eco-routing serves as an intermediate and are investigated for both conventional and electric vehicles. For the latter, constant speeds are also crucial for the powertrain to run as efficient as possible. Several studies point out the significant energy savings that can be accomplished in this way ([26]–[28]). Next to trip characteristics, the road type also determines emissions. As such, it is obvious that flat surfaces without inclinations, changes in speed limits or intersections lead to lower overall emissions. There is, nonetheless, a compromise between the topology of a region and the number of kilometres that needs to be covered to avoid demanding routes. Despite the fact that hilly routes can substantially add to the overall trip emissions, opting for a detour does not always belong to the options of a driver.

3.1.6 Other

Other factors impacting both fuel consumption and pollutant emissions are mainly those influencing the driver cabin climate and vehicle aerodynamics. As such, **air-conditioning** (A/C) is known to be a substantial source of extra emissions, given its additional energy consumption ranging up to 6 kW power, equivalent to driving a car steadily at 56 km/h[15]. Several studies have compared the use of A/C with opening the car windows for ventilating and bringing down cabin temperatures. The outcomes suggest that rolling down windows is a more energy efficient choice at lower driving speeds, for instance during city driving, while A/C becomes more efficient during motorway speeds. During the latter, the extra fuel consumption and resulting pollutant emissions due to a strongly reduced aerodynamic drag when windows would be rolled down at higher speeds outdoes the extra consumption following the work that has to be delivered by the A/C system. Cabin temperatures and the A/C demand at the start of a trip can further be influenced by where a car is parked, e.g. in a shaded spot on hot days and covered on cold days. Finally, tyre inflation, avoiding excess (‘dead’) weight in the car due to unnecessary cargo and exterior parts influencing aerodynamics are highlighted, as will be discussed in the preliminary insights from WP2.

Based on what can be found in literature about eco-driving, we have to conclude that pollutants are more than often not included in the analyses which typically focus on CO_2 and fuel consumption2018). Moreover, such studies mainly look at individual vehicles, ignoring pollutant emissions and impacts on network levels. Within the uCARe project, there is the ambition to overcome this deficiency by focusing on pollutants and deriving so-called ‘delta emission factors’ (emission reduction potentials) from pilot studies performed across the EU, assessing the likeliness of pilot participants for maintaining the trained measures to reduce their impact on local pollutant emissions, and extrapolating these findings for several EU member states.

4 Quantification of emission reduction potentials

Largely, the quantification of these emission reduction potentials relies on either measuring them while a vehicle is being used or by simulating it. Measurements can take place in various contexts. Thus, vehicles can be set-up on a chassis dynamometer test bench to perform driving cycles with specific driving styles. Whereas this type of testing has proven its worth in terms of comparing CO_2 emissions of different vehicles, e.g. passenger cars, laboratory settings will always remain artificial as unpredictable external influences like traffic density and climatological changes are difficult to incorporate in the test. In terms of pollutants, the 2015 diesel scandal also made clear that solely basing type-approval tests on lab tests using roller benches paves the way for fraudulent strategies by vehicle manufacturers to recognise test situations and to calibrate the emission control system to work optimally in these conditions (only). Therefore, on-road testing using portable emissions detection devices such as PEMS and SEMS has seen increased interest since the early 2010s as significant deficiencies with lab test results came to light. Real-driving emissions (RDE) testing became part of the heavy-duty type-approval program since December 31st, 2013 (Euro VI) and for passenger cars since September 1st, 2017 (Euro 6d-Temp). Testing vehicles during their actual use is a cost- and time-consuming activity that leads to a rather low test population EU-wide. SEMS have the potential to drastically upscale this population although these simplified PEMS systems currently only exist in the Netherlands and are not yet applied on a large scale elsewhere. PEMS and SEMS offer the highest detail in vehicle emissions (typically registering CO_2, CO, HC, NOx and PN) and the traffic conditions they are in (road grade, GPS coordinates, etc.).

A cheaper option for PEMS and SEMS is to equip representative fleets with data loggers connected to the vehicle's onboard diagnostics systems (OBD). As such, vehicle and engine speeds can be registered, while for the more recent vehicles emission-related sensor data can be retrieved as well. Within uCARe, a small test population of about 10 passenger cars will be installed with such loggers to give the drivers real-time feedback on how their driving style may be altered in favour of lowering pollutant emissions.

Remote sensing has the potential to scan entire fleets in a very cost-efficient way, although it has the limitation of taking only instantaneous snapshots of a vehicle's emissions, hence not allowing to distinguish driving styles nor to obtain gear-shift data. This is especially due to the location bias as remote sensing units are typically implemented by the side of roads with a certain inclination, making sure that the vehicles passing by are being accelerated.

Another way is to model entire powertrains in a virtual environment and to feed speed-time data to this model. To validate models with reality, data from PEMS tests can be run to see to what extent similar emission levels can be reached through the model. Project partner Technical University Graz (TUG) has been developing models for powertrains since the late 1990s, with the Passenger Car and Heavy-Duty Emission Model (PHEM) resulting from these efforts. PHEM is an instantaneous emission model based on equations of vehicle longitudinal dynamics and engine emission maps. As such, it calculates the fuel consumption and emissions of road vehicles in 1Hz (on a per-second-basis) for a given driving cycle. The engine power demand is calculated in 1Hz for the cycles from the driving resistances and losses in the transmission line. The engine speed is simulated by the tyre diameter, final drive and transmission ratio as well as a driver gear shift model. Base exhaust emissions and fuel flow are then interpolated from engine maps. The Handbook of Emission Factors for Road Transport (HBEFA, INFRAS et al. 2014) defines typical driving cycles for all relevant traffic situations and vehicle categories and uses PHEM to produce the corresponding real-world emission factors. The COPERT model also uses hot emission factors derived from HBEFA. By making the model modular (cycle, vehicle data, engine map are individual files) one can simulate variations of a given vehicle (same vehicle with different cycles or vice versa; or same vehicle but variation of engine maps (euro5, euro6ab, euro6d-temp)). Insights from the PHEM model concerning the impact of the vehicle set-up will be discussed in chapter 6.

5 The ecoDriver project (2016)

The 2012-2016 ecoDriver project shows a strong correlation with the mission of uCARe [29]. In the former project, driver behaviour was monitored and steered towards higher energy efficiencies whilst driving. Although pollutant emissions were not the main focus of the project, important parallels can be drawn on which uCARe can build. Similar to the uCARe approach, ecoDriver focussed on in-drive and post-drive instructions to improve one's driving behaviour. Therefore, a model was developed for real-time optimisation of energy use and applied on cars, vans, trucks and buses. The applied measures varied from smartphone applications to elaborate devices and included both aftermarket fitments and original equipment manufacturer (OEM) designs. Also, a 'full ecoDriver system (FeDS)' was developed to serve as an example for the human-machine interface (HMI) design and energy calculation software, based on a full set of sensors.

Starting point arguments for the ecoDriver project were that existing (pre-2012) systems did not consider upcoming road alignment, influential factors like distraction were not yet investigated and the acceptance of systems and their designs were largely unknown, also for post-drive feedback. Moreover, there was an interest to investigate to what extent nomadic systems (e.g. TomTom) could be improved in terms of feedback to the driver and how such would score compared to integrated OEM systems. Therefore, objectives were set out on how to best 'win' the driver's support for best energy efficiency driving behaviour, aiming at the whole road transport sector to apply the innovative system. Specific interest went to how the support system would affect a driver's attention whilst driving. Whereas most focus went to energy efficiency and CO_2, ecoDriver also looked at pollutants. Together with TomTom, a calculation tool was built to assess the driver advice for the road ahead (slopes, bends, etc.). This tool was adapted to the different powertrains.

Real-world trials showed that real-time information yielded better advice towards the driver rather than giving instructions after a trip. Significant energy savings were yielded as well as substantial improvements in speed compliance leading to large safety benefits. In terms of reduction, an overall energy use reduction of 4.2% was achieved, with even higher (5.8%) benefits on rural roads. In terms of cruising speeds and on the approach to events such as sharp curves, a 4% speed reduction was reached. Concerning hazardous pollutants, a 4% NOx reduction was yielded on average, with a range from 2,6% (urban) to 5,1% (rural). On motorways, the reduction amounted to 3,4%. When comparing feedback systems to drivers, higher CO_2 (6%) and NOx (5,7% rural) reductions were obtained with embedded systems (relying on the vehicle's CAN data) than with the smartphone application. Haptic throttle pedals were found to provide substantial effect on energy consumption (and thus, indirectly on pollutants although this has not been quantified). In terms of the advice that was given to drivers, a balance was sought between a theoretical optimum and what was acceptable for drivers. As such, recommendations for driving at speeds well below a (high) speed limit generally lead to low acceptance. As a rule of thumb, a 100 km/h speed was recommended when higher (motorway) speeds were allowed. In terms of safety, the driver was often advised to slow down when nearing intersections, sharp curves or preceding vehicles, rather than to maintain the current speed. As such, safety was prioritised over emission savings.

Similarities between ecoDriver and uCARe are that in the latter project, we try to advise drivers on covering their trips in the least-polluting way. Therefore, gear shifting improvements, as well as avoiding harsh accelerations and decelerations will be advised to drivers to improve eco-driving. The difference with most studies performed earlier, however, is that with uCARe the focus is clearly on pollutants and less on energy efficiency. In the following chapter, we will focus on the pollutant reduction potentials that have been quantified so far (i.e. December 2020).

6 uCARe measures and their reduction potential

In the absence of results from uCARe pilot projects, a ranking of uCARe measures can be based on different sources of information. As such, two important tracks of reduction potentials can be provided, namely a pre-trip checklist on how vehicles are set-up, and an exercise based on integrating existing real-driving emissions (RDE) data into a uCARe model for assessing the relative reduction potential between the trip how it was actually driven and (super) eco-driving. This model is currently being validated with 5 passenger car models that have been thoroughly tested by TUG using chassis dynamometer and PEMS emission tests. These vehicles have subsequently been rebuilt in a virtual environment to model their emission impact if driving styles and vehicle set-ups would be altered. Through this step of feeding the model with real-world testing data from earlier work, we obtain first insights into the potential of pollutant emission reductions.

At this stage (December 2020) a first round of validations is finished. Based on RDE data, vehicle speed, engine speed and vehicle altitude data have been fed to the model, which then calculates how the vehicle was driven (eco, normal or aggressive) and provides an output consisting of the CO_2 emission, fuel consumption and pollutant emission factors (g/km) for NOx, CO and PN. In a next step, a feature will be developed to allow for the model to suggest the driver to change certain aspects of his/her driving style to reach a better environmental performance. This may be a gear recommendation, a request to accelerate/decelerate differently, etc. For the estimation of the pollutant emissions, the driver will be asked to be as specific as possible for the vehicle characteristics (make, model, Euro class, fuel type) and the existing set-up (summer/winter tyres, roof rack, bicycle rack, etc.). Based on augmented emission maps previously developed in uCARe, emission factors can then be developed based on the CO_2, vehicle speed, altitude and engine speed data that is fed to the model. These emission maps will ultimately include cold start extra emission (CSEE) impacts and the consequences of poor maintenance, deterioration and illegal tampering of/with emission control systems.

6.1 Conceptual framework for quantifying emission reductions

In uCARe, we quantify emission reduction potentials from measures an individual driver or vehicle owner can implement as follows:

ER = DeltaEF * Beta * Gamma

With

- ER = Actual emission reduction of a given measure (e.g. defensive driving style) with a given vehicle type (e.g. Euro-5 Diesel PC) in a given traffic situation (e.g. an urban main road with 50 km/h speed limit, in free-flow conditions)
- DeltaEF = Potential emission reduction
- Beta = Percentage of drivers that will implement the measure in day-to-day driving
- Gamma = Percentage of effectivity to which drivers implement the measure on average

It should be noted that the DeltaEF, i.e. the “potential” emission reduction, and the Gamma factor, are somewhat complimentary. As such, the maximum potential reduction of e.g. a defensive driving style may be achieved with a degree of defensive driving that is not realistic in on-road circumstances since it would slow down the driver – and the other traffic participants – too much. A realistic Gamma factor would then have a low value. Conversely the “maximum” may be defined as not overly defensive – but then Gamma factors of >100% may be possible. This flexibility does not represent a problem as long as we explicitly state cycle parameters such as average speed, relative positive acceleration, stop time, or other appropriate parameters (or the changes with respect to a “base” cycle corresponding to “normal” driving) associated with a given DeltaEF. The set of parameters to be associated with a given DeltaEF is yet to be elaborated in WP4 of uCARe.

6.2 Vehicle set-up parameters and their impact

In Table 6-1 an overview is given of standard configuration for the rolling resistance of the tyres (Fr_0) and the aerodynamic drag coefficient (Cw)for a BMW 218d, as a reference vehicle. Results for the changes in the vehicle set-up, shown in Table 6-2, influence both CO_2 and pollutant emissions. In this exercise, we will look what these vehicle settings mean for the BMW 218, while in WP2 the impact on a Euro 5 petrol and diesel car, as well as on a Euro 6a,b petrol and diesel car are calculated. The results for the exemplary BMW 218d are also and shown graphically in Figure 6-1.

Table 6-1 Exemplary standard configuration for a BMW 218d, for rolling resistance Fr_0 and drag coefficient Cw

BMW 218d	Fr_0	cw
Standard configuration	0.009359	0.3084

Table 6-2 Overview of the impact of different vehicle set-ups, for rolling resistance Fr and drag coefficient Cw, and the relative impact on CO_2, CO, NOx and PN for the BMW 218d, ranked from smallest to largest impact (reductions to increases)

	Emission variations (%)					
	Fr_corr [%]	Cw_corr [%]	CO2 [g/km]	CO [g/km]	NOx [g/km]	PN [#/km]
Summer tyres low loading	-3.70%	6.50%	-4.31%	-1.75%	-16.00%	-2.14%
Summer tyres high pressure [1]	-3.50%	-0.40%	-0.74%	-0.60%	-1.33%	-0.97%
Summer tyres open windows	0.40%	3.80%	1.21%	1.46%	2.88%	2.36%
Summer tyres roof rack	0.30%	7.90%	2.40%	2.57%	6.52%	4.49%
Summer tyres PEMS on trailer hitch	0.60%	9.30%	2.98%	3.17%	8.04%	5.36%
Summer tyres PEMS in trunk	1.60%	9.30%	3.03%	3.22%	8.16%	5.43%
Winter tyres high pressure [1]	1.70%	10.40%	3.42%	3.76%	9.29%	6.38%
Summer tyres low pressure [2]	3.70%	9.70%	3.51%	3.74%	9.09%	6.30%
Summer tyres wind	2.90%	15.90%	5.17%	5.94%	14.34%	10.18%
Winter tyres standard pressure [3]	11.90%	10.70%	5.30%	5.61%	12.66%	8.94%
Summer tyres wet street	24.00%	11.80%	7.95%	8.11%	18.20%	12.99%
Winter tyres low pressure [2]	19.10%	17.90%	8.91%	9.60%	21.24%	15.37%
Summer tyres rain	24.10%	17.00%	9.54%	10.09%	22.29%	15.94%
Summer tyres roofbox	5.30%	27.50%	9.72%	12.08%	27.96%	19.43%
Summer tyres bike rack	2.60%	62.50%	19.50%	22.74%	64.23%	30.38%

Summer tyres trailer	6.90%	102.30%	33.16%	28.25%	126.78%	42.54%

[1] *High pressure = Front 3.1 bar / Rear 2.9 bar,* [2] *Low pressure = Front 2 bar / Rear 1.8 bar,* [3] *Standard pressure: Front 2.6 bar / Rear 2.4 bar*

A graphical representation of the impacts given in Table 6-2is shown in Figure 6-1. Note that for both CO_2, CO, PN and NOx emissions, a low loading of the car, i.e. by removing all unnecessary 'dead' weights in the vehicle results in a substantial reduction compared to the standard configuration. Whereas underinflated summer tyres generate a 9% extra NOx emission, properly inflated winter tyres cause a 12.7% increase. If these are underinflated as well, extra NOx emissions amount up to 21%, indicating the impact tyre selection and pressure has on NOx. Typical measures that worsen a car's aerodynamic drag, such as roof boxes, bike racks and trailers, negatively impact both CO_2 emissions and the considered pollutants. For NOx, this impact increases significantly in case of bike racks and trailers.

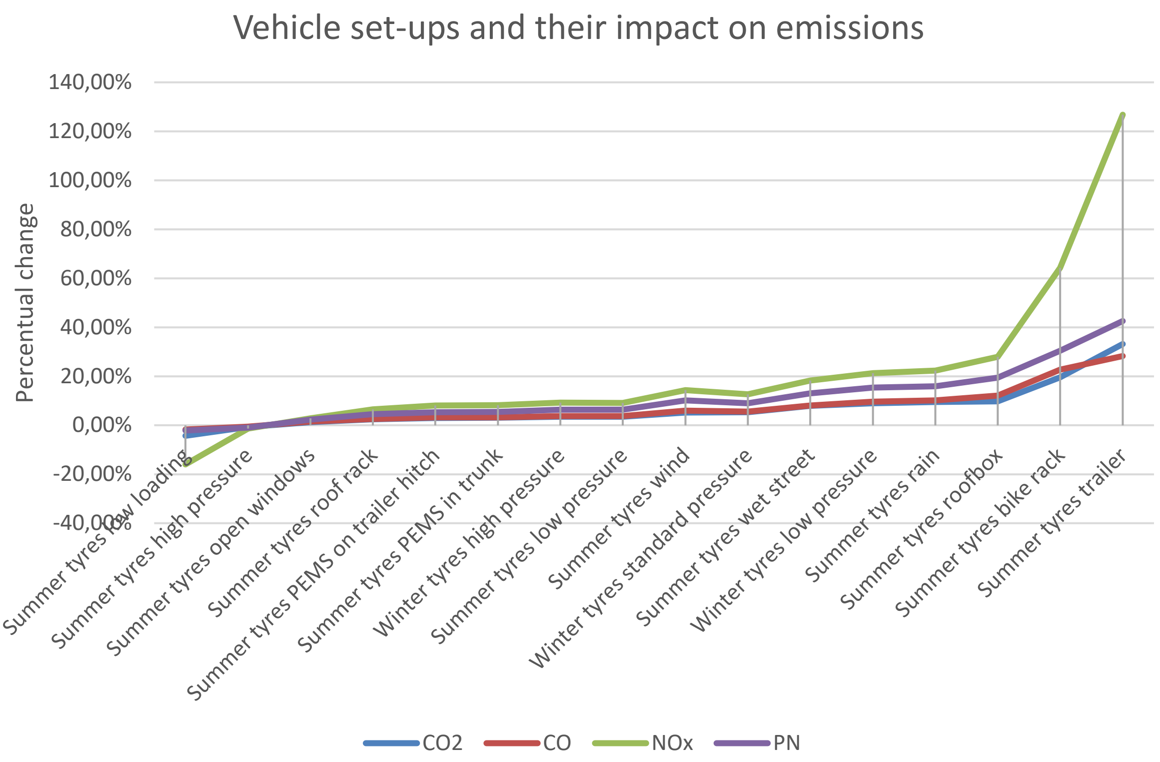
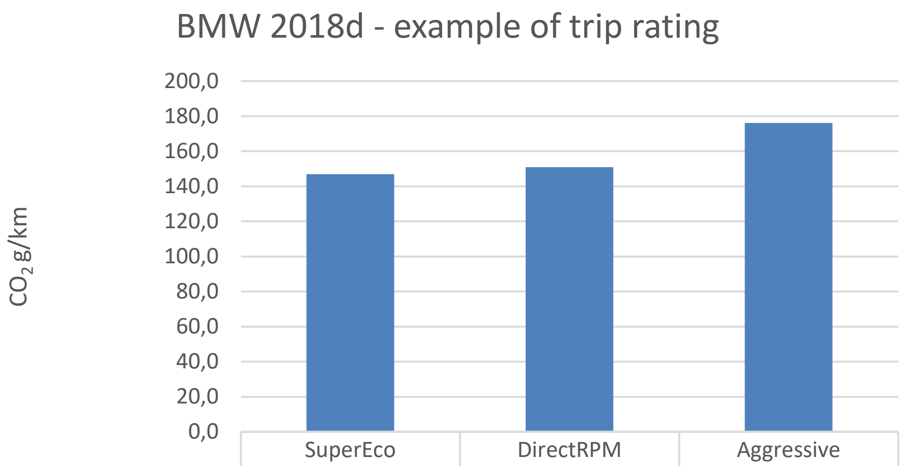


Figure 6-1 Graphical overview of the percentual changes per set-up measure and its impact on the different emissions

This example of the BMW 218d shows how similar impacts will be generated from the pilots as soon as measured data comes in. As such, the impact of a specific vehicle's set-up will be incorporated in the augmented emission maps to show the driver how personal driving behaviour can effectively have an influence on pollutant emissions. Here, the aim is to cover as many different vehicles models as possible to distinguish impacts between combinations of Euro Classes, fuel types, engine types, etc.

6.3 Potential reductions from switching from aggressive to eco-driving

Based on the exercise of feeding the uCARe model with RDE data from previous PEMS test campaigns, the objective is to rank trips based on their difference to how they could have been driven in an eco-friendly (i.e. 'SuperEco') way. Therefore, the model calculates from the actual trip data how much of a selected pollutant is emitted. This is referred to as the 'Direct RPM' result in Figure 6-2. Next to that, a so-called 'SuperEco' and an aggressive way of driving the same trip is simulated, based on smoother/harsher accelerations and optimised/worsened gear shifting, respectively. As can be seen in the example in Figure 6-2, the actual trip was driven in an ecologic way, hence the small difference with the simulated 'SuperEco' mode. By feeding aggressive trip data to the model for this specific modelled vehicle, we can determine the potential reduction between the aggressive mode and the super eco mode. This potential will be the output of the model when pilot data (CO_2, vehicle speed, engine speed, altitude) is used as input, and will allow for a ranking based on driving styles. Additionally, the vehicle set-up parameters will be included in this impact assessment.



	SuperEco	DirectRPM	Aggressive
CO2 [g/km]	146,8	151,0	176,2
Delta to Direct RPM	97%	100%	117%

Figure 6-2 Example of how the difference between a Super Eco and aggressive trip with the Direct RPM input is determined for the BMW 218d

For the validation of the uCARe model, a substantial set of driving cycle data was provided. This set consists of trips with aggressive driving behaviour derived from Worldwide Light-vehicles Test Procedure (WLTP) data (239 trips from 25 vehicles), PEMS tests (210 trips from 3 Euro 4 vehicles) and trips ran in the urban and sub-urban Aachen region with different driving behaviour (from 11 different vehicles). This trip data was fed into a model representing 5 vehicles that have been tested thoroughly and rebuilt virtually. Examples of emission reduction potentials derived from the data from the first 50 trips performed by one of the diesel passenger cars are given below. Note that for NOx emissions, the large variety in the originally monitored driving behaviours results in a substantial spread in potential reductions when the trip data is re-run by the modelled diesel car. As such, trip nr.10 was driven in a very NOx-friendly way, whereas the subsequent trip shows a reduction potential up to 70% if it were driven in a super eco way. For CO, the examples show that the potential reductions are rather marginal although CO emissions are typically very low for diesel cars. For PN emissions, we report for certain driving styles that a super eco mode would result in actual increasing emissions.

These impacts, as well as a way to rank vehicle driving styles for providing feedback to the driver, will be further elaborated and updated in the next version of this deliverable. Also, a further characterisation of the trips in terms of the shares of urban, rural and motorway driving will take place. This will allow to disaggregate trips to specific HBEFA traffic situations, so specific emission reduction potentials per such situations can be estimated.

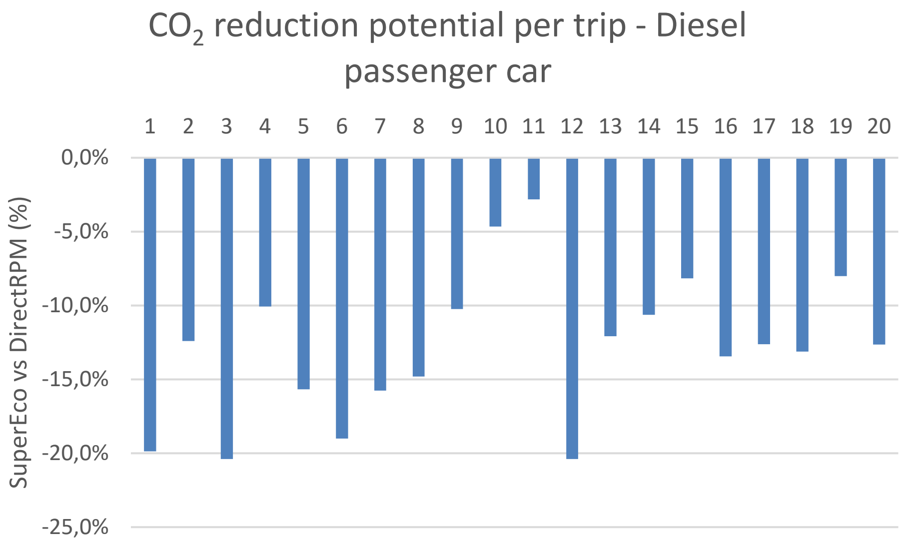


Figure 6-3 Diesel passenger car CO_2 reductions per simulated trip

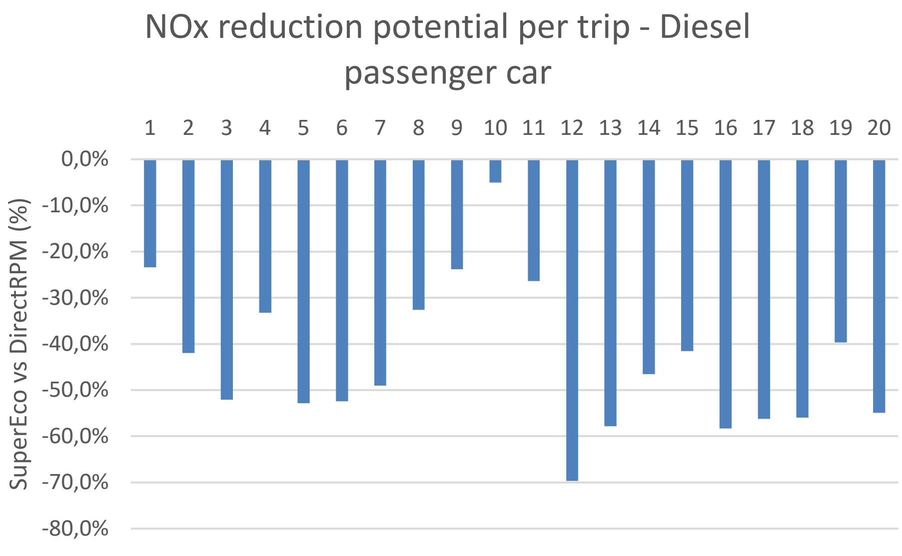


Figure 6-4 Diesel passenger car NOx reductions per simulated trip

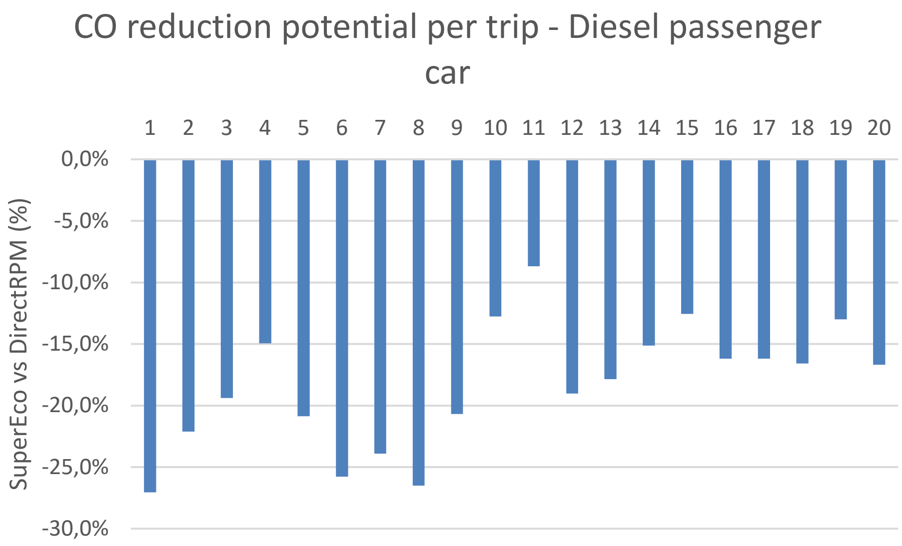


Figure 6-5 Diesel passenger car CO reductions per simulated trip

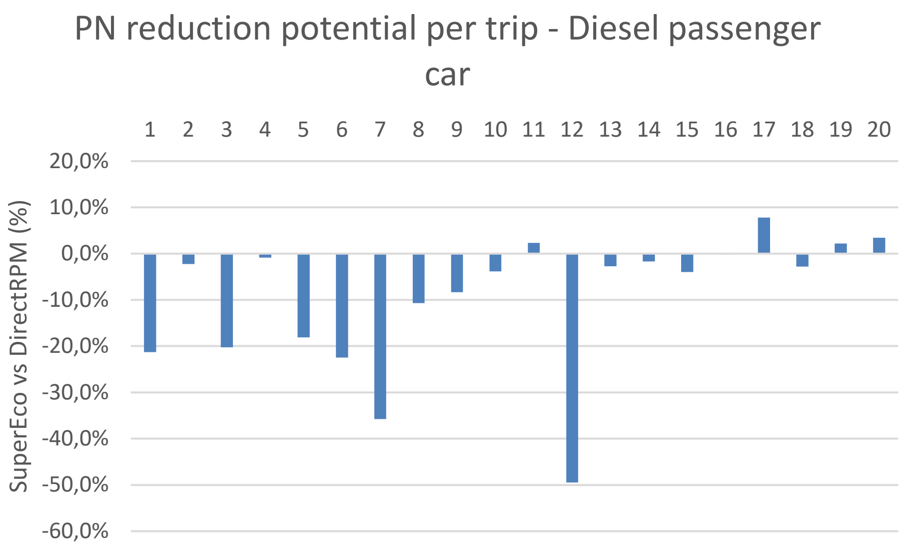


Figure 6-6 Diesel passenger car PN reductions per simulated trip

7 Conclusions and recommendations

In the December 2020 version of this deliverable on the reduction potentials for hazardous pollutants, we started with a literature review on 'eco-driving' and how pollutants are generally left out of investigations led by other researchers. In that viewpoint, uCARe will bring new insights to the common knowledge by focussing on how excessive emissions by the existing road vehicles fleet can be tackled. The human factor in this exercise proves to allow for a significant reduction potential by means of education on how specific vehicles should be driven to minimise their impact on local air quality. Driver education and systematic following-up or refreshing of alternative way to power a vehicle are low-cost means to bring down pollutant concentrations, especially when compared to altering road infrastructures or imposing stricter emission legislation for new vehicle models.

Whereas no pilot data was available yet at the time of writing this deliverable, methodologies for ranking uCARe measures according to their pollutant reduction potential have been set out, based on the insights from the modelling work done in WP2. In the course of Spring 2021, a first update will be performed based on pilot data.

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