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TNO report

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Environmental Benefits of C-V2X for 5GAA - 5G Automotive Association E.V.

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Abbreviations List

Abbreviation	***Explanation***
3GPP	3rd Generation Partnership Project
5GAA	5G Automotive Association
ACC	Adaptive Cruise Control
ADAS	Advanced Driver-Assistance Systems
CACC	Cooperative Adaptive Cruise Control
CAD	Connected Automated Driving
C-ITS	Cooperative Intelligent Transport System
CO_2	Carbon dioxide
C-V2X	Cellular-Vehicle-to-Everything communication
D2D	Device-to-Device
DSRC	Dedicated Short Range Communication
EV	Electric Vehicle
FCW	Forward Collision Warning
FEA	Fuel Efficiency Advisor
ICT	Information and Communication Technology
LTE	Long Term Evolution
MEC	Multi-access Edge Computing
NO_x	Nitrogen oxides
OBU	On-Board Unit
OEM	Original Equipment Manufacturer
PM	Particulate Matter
TSP	Traffic Signal Priority
UE	User Equipment
V2I	Vehicle to Infrastructure communication
V2N	Vehicle to Network communication
V2V	Vehicle to Vehicle communication
V2X	Vehicle to everything communication
VRU	Vulnerable Road User

1 Management summary

There is increased interest in the potential environmental benefits of C-V2X, given that substantial transport emissions reductions are required to help mitigate climate change, and the upcoming EC Strategy on Sustainable and Smart Mobility which intends to propose matching measures to the "unprecedented ambition to achieve 90% reduction in emissions by 2050". The question is to what extent connected driving, with increasing levels of automation, can lead to environmental benefits. 5GAA, the 5G Automotive Association, asked TNO to conduct a study into the environmental effects of V2X communication as it is currently used in transport and as it can be used in future implementations.

The overall goal of this study is to provide insights into the emission reduction potential of C-V2X large-scale deployment including and beyond day 1 services.
Emphasis is on communication to and from the vehicle. In particular, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I or I2V) applications. The focus is on the environmental effects of applications in traffic using communication technology, not on the specific type of communication technology that is used. The time horizon is 2050: the study looks at evidence from existing applications, but also considers promising use cases that may only be realized several decades from now. Only direct environmental impacts from traffic and transport are considered, not additional energy use for e.g. energy use of back-offices or energy and resources needed for the production and operation of C-ITS systems.

The study comprised several steps to identify promising use cases: a review of the available literature on the environmental impact of C-V2X use cases, interviews with stakeholders about potential future use cases with expected substantial benefits, and identification of promising use cases based on how travel behavior and driving dynamics can be influenced. The resulting list of promising use cases (see chapter 5) shows that there is potential for C-V2X services to reduce emissions at several levels: targeting driving dynamics of individual vehicles, traffic flow management or travel behavior such as transport mode choice, destination choice, departure time choice or the choice to make a trip or not. Benefits will not emerge from communication technology directly, but from communication-facilitated transformations at all levels (proper application deployment strategies, triggering of travel behavior changes, smoothening of traffic flow).

The specific elements of the current study approach are the following:

A. Literature research, which included looking for evidence of the reduction potential for various use cases in past projects and studies;
B. Interviews with stakeholders about potential future use cases with expected substantial benefits;
C. Identification of promising C-V2X use cases, in addition to those found in literature;
D. Impact analysis. This includes both qualitative and quantitative analysis. The latter is performed also with TNO emission tool "EnViVer", to further explore the potential of some of the promising use cases;
E. System level analysis, which includes the possible implementations with current and future communication technologies.

The reduction potential of C-V2X services has been shown in various real-world pilots, driving simulator studies and traffic simulation studies. In addition to results found in literature, we carried out indicative calculations with a microscopic emission calculation tool (EnViVer), using speed patterns data from real-world pilots and microscopic traffic simulations carried out by TNO. We used hypothetical speed patterns to illustrate the potential of future use cases where vehicles drive with minimal dynamics (enabled e.g. by coordinated movements between vehicles). We also analyzed how the identified C-V2X services could be deployed considering the available communication technologies as well technologies expected for the future.

Several impact mechanisms have been considered in this study, in order to express how the reduction of emissions can be achieved. These impact mechanisms are related to existing inefficiencies of the transport and traffic system, which appear either pre-trip or on-trip. The identified mechanisms are the following (see for a more elaborate description Table 1 on page 12):

- Reduction of trips;
- Reduction of kms driven and/or departure time shift;
- Modal shift;
- Reduction of vehicle dynamics;
- Powertrain operation.

The calculation and prediction of expected impacts are based on different approaches, including real data collection (field operational tests, deployments on diverse scales), modelling approaches, including extrapolated or scaled-up data, or even estimations coming from expert judgement and from state-of-the-art overview reports. Therefore, the data types and results, as well as their reliability, transferability and scalability can vary broadly.

The main purpose of the **literature research** part of the study was to identify state-of-the art projects, which indicate existing promising use cases, leveraging (C-)V2X for environmental benefits.
The first step in the literature research was to make an overview of use cases mentioned in several literature review studies and long reports, and their associated environmental impacts. A set of thirty studies was included in a longlist. Studies include EU and US projects, national or local projects for public authorities, industry, research institutes, universities etc. The selected ones focus on quantitative, validated data, rather than expert opinions.
Out of the longlist, a shortlist was selected based on promising results, adequate information on implementation and results of use case, satisfactory approach, and the reliability of identified impacts. The final shortlist consists of 10 reports and papers (see Table 2 on pp. 15).

Figure 1 shows the range of effects, expressed in CO_2 emission reductions, as described in the literature, classified per level in which the impact is described.

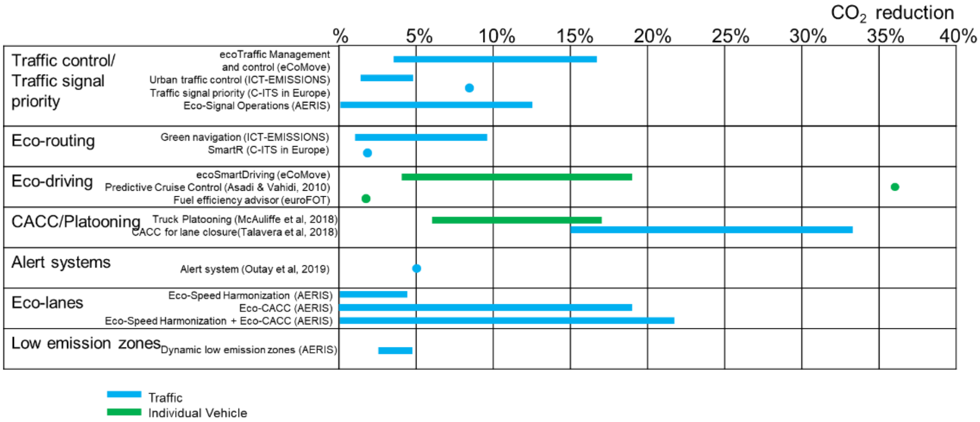

Figure 1: Impacts of different applications classified per level on which the impact is described.

What stands out from the literature research is the fact that most of the case studies providing quantitative results on environmental impacts are focused on applications for on-trip purposes. These are most commonly achieved due to smoother traffic and reduction of in-vehicle dynamics. Therefore, the center of attention of these cases has been the vehicle level but in most of the cases, the impacts are assessed on a traffic level, which offers a better perspective on the real potential. Very often the studies suggest the combination of different services and applications for the achievement of better results, implying the need for communication technologies able to facilitate concurrent services with different requirements on the network, such as minimum bandwidth and maximum allowed latency. Most of the studies have used simulation as a tool, and much less often field studies with test vehicles in real-world, although some of the approaches included first a field study and then used simulation for scaling up the results. The results differ widely due to diverse conditions in testing, in terms of penetration rates, road types and network environment, time of the day etc. The denser traffic is, the more difficult it is to keep driving dynamics at a minimum. Cooperative services such as CACC and shockwave damping can be very effective also in busy traffic, but results depend on the penetration rate (and headways settings). All this explains why smaller and larger effects were found for the same services.

The main purpose of the **interviews** was the collection of extra information and reference sources, derived directly from experts in the field of connectivity and communication technologies. Interviewees were asked which promising use cases (services, applications, etc.), using connectivity in traffic (V2V, V2I, V2N), they foresee and how these are expected to result in environmental benefits. The interviewees were selected such that there was a good spread over OEMs, road authorities, traffic experts, consultants, industry and academia as well as over different geographical areas. In total, 10 on-line interviews were carried out. The interviewed organizations are the following:

- Robert Bosch GmbH (Mobility Solutions)
- European Automobile Manufacturers' Association (ACEA)
- BMW Group
- Delft University of Technology (department Transport & Planning)
- Bishop Consulting
- ERTICO – ITS Europe
- Federal Highway Research Institute (BASt)
- Agora Verkehrswende (Environmental consultant)
- Tongji University (College of Transportation Engineering)
- Finnish Transport and Communications Agency (Traficom)

The overall conclusions that came from the interviews is that a long-term vision of the transport system is hard to be conceived and envisaged right now, however the role of better, more direct communication technologies that allow the cooperation and coordination of all road users and infrastructure is definitely valuable, in order to achieve the best environmental impacts. The current view on the environmental benefits is not very clear, due to differences in the services offered and applied, as well as the penetration rates. A shared view by all the interviewees was the potentially large, but still uncertain, benefits due to modal shift, and a high potential for a scenario where all road users and traffic management systems are connected to each other to optimize traffic flow. This so-called “everything connected to everything” use case is a concept, to be established by the implementation of numerous use cases. The effect which can be gained by it consists of the combined effect of all these individual use cases.

The list with promising use cases, resulting from the literature review, interviews and our own expertise, is the following:

- Automated intersection crossing
- Bike-to-everything
- Continuous Traffic Flow via Green Lights Coordination

- CACC
- Cooperative Lane Merge
- Cooperative Driving Maneuver
- Dynamic Geofencing
- Dynamic pricing
- Dynamic ride sharing
- Eco-trip planning
- En-route/ on-trip (eco-driving) advice
- “Everything connected to everything”
- Flexible road use (e.g. Dynamic tidal flow lanes)
- Continuous Traffic Flow Green Lights Coordination (priority request for high emitters)
- Group Start
- Location-based automatic switches hybrid to electric
- On-street parking service
- Real-time optimal route advice
- Shared mobility route planning
- Shockwave damping
- Speed Harmonization
- Traffic Jam Warning and Route Information
- Vehicles Platoon in Steady State

The promising use cases have been categorized according to the impact mechanisms as described before (see Table 10 on pp.30), as well as with respect to the level on which the application acts (see Table 9 on pp. 28). Three levels have been identified and used throughout the current study: the vehicle, the traffic and the system level. Applications related to the operational level of driving and which mostly affect the vehicle dynamics, belong to the vehicle level. Others, which affect the overall traffic flow and network and are more related to the tactical level of driving, correspond to the traffic level. The system level pertains mostly to cases where strategic decisions of road users are influenced, e.g. the route choice.
What is interesting to note, is that the majority of use cases falls into the vehicle level. As already mentioned, most of the potential is currently explored and identified in ‘on-trip’ applications, with a focus on reducing vehicle dynamics. Some use cases, such as the Cooperative Driving Maneuver, belong to more than one level. The use case “Everything connected to everything” is found on all levels, since it is a combination of all promising use cases.

In addition to the impacts found in the literature, for important use cases for which no reliable impact estimates were available, additional **indicative emissions calculations** have been performed. The following 4 use cases represent a large part of the earlier presented promising use cases, and are selected as the basic use cases for the impact assessment:

1. CACC
2. Eco-driving on motorways (including avoiding congestion)
3. Intelligent intersections
4. “Everything connected to everything”

Different types of data sources have been used for the impact assessment, namely pilot data, real-world data, data from microsimulations and synthetic data, as described in paragraph 6.2.

For the impact assessment, the TNO emission assessment tool EnViVer was used. It is based on vehicle emission models for 400+ detailed vehicle classes (Dutch fleet). The results of this indicative impact analysis with real-world, simulated and synthetic data show that avoiding stops in any way is very beneficial (CO_2 emission reductions in the range of 13-45%, depending on the speed limit and number of stops per km). Reducing the driving dynamics (amount of deceleration/acceleration) shows reductions in the range of 3-7% in situations where reducing driving dynamics is possible (note that this becomes more difficult the higher the traffic densities are). Services helping to avoid congestion could reduce emissions by 6% (extra emissions caused by congestion). Going from ACC to CACC also showed emission reduction effects of about 6%, due to less vehicle dynamics. N.B. The effect of aerodynamic drag reduction, when driving closely together, possible with CACC, is not included in this result.

Considering the expected evolution of connectivity and increasing levels of experience with (and potential integration of) C-V2X applications, also for emission reduction purposes, it can be assumed that the effectiveness of services will increase over time. For each part of a trip, services are available that can help reduce emissions.

Given that reductions in emissions in the order of magnitude of 5%-20% were found (at the local traffic flow level, resulting from various promising use cases), and that we found a similar range with our indicative impact analysis, it can be argued that if C-V2X services become available on a much larger scale and are geared towards emission reduction, they can contribute substantially to the reduction of CO_2 (and other) emissions. In an “everything connected to everything” scenario, emission reductions are possible for each part of a trip that motorized vehicles make. In addition to that, having ubiquitous, high-bandwidth and low-latency connectivity that enables e.g. MaaS and logistics services, can also help travelers and freight companies make choices that result in avoided trips, change trips to different times of the day (e.g. at nighttime, for truck platooning) or lower mileage (working from home, using a bicycle and/or train instead of a car, using an electric shared vehicle instead of an own car, sharing rides, etc.). MaaS, ride sharing, and other shared mobility services are therefore also very promising use cases for reducing emissions.
However, in cases where C-V2X services lead to much improved traffic flows on previously congested routes (resulting in substantially improved travel times), this can also lead to the generation of more motorized traffic (latent/induced demand). This could result in increased emissions. Also, if automated driving reaches higher levels and, for instance, automated taxis would become a very popular means of transport~~,~~ this could result in higher mileage and more emissions (however, this also depends on the powertrain/energy carrier of the vehicles). As for instance mentioned in Wadud et al. (2016): The overall energy and environmental implications of automation in the future will depend upon:

- The degree to which energy-saving algorithms and design changes are implemented in practice.
- The degree to which automation actually leads to system-wide changes that facilitate energy savings, e.g. shared vehicles, adoption of alternative propulsion technologies and fuels.
- The degree to which reduced driver burden (and reduced cost of time spent in the vehicle) leads private travelers to spend more time and travel greater distances in their vehicles or leads to greater commercial roadway activity.
- Policy responses at the federal(/national), state(/regional), and local levels.

It should also be noted that many services also have benefits in other areas, such as traffic safety or traveler’s comfort. In fact, quite some services which were analyzed on their emission reduction potential were designed for traffic safety and/or traffic efficiency. This also implies that future (C-V2X) services, not primarily designed for emission reduction, will nevertheless generally have emission benefits. Traffic safety, traffic efficiency and traffic sustainability are all connected.

Developments in vehicle propulsion and design also need to be considered when looking at the emission reduction potential of promising use cases.
In the future, the traffic composition will change, with an expected higher share of “cleaner” (hybrid or fully electric) vehicles. Thus, both the absolute and the relative impacts will change. Also not considered in this study are aspects such as vehicle downsizing/resizing, CO_2 emissions as a result of manufacturing (less) vehicles, and the carbon footprint from 5G deployment.

The **system level analysis** of this study has shown that different implementations, using different (combinations of) communication technologies are possible for the deployment of the C-V2X services. The added value of connectivity for sustainable goals can be gained in several ways. Much is possible already now with the current existing long- and short-range communication technologies, such as LTE, LTE-V2X and ITS-G5. It is important to realize that under the 5G umbrella (the 3GPP roadmap) new features can become available in the near future, suitable for deploying multiple concurrent services with different requirements. Concurrent services have requirements such as:

- Minimum bandwidth: new frequencies and technologies can provide sufficient bandwidth for multiple, more advanced services;
- Guaranteed performance: Slicing enables better Quality of Service for individual V2X services without interference of other concurrent services, like ‘regular’ Internet services;
- Maximum allowed latency.

The 5G architecture as shown in chapter 7 allows for a scalable implementation, with both local (edge servers) and national (central servers) components, and short- and long-range communication. The different requirements of the services (maximum allowed latency, minimum required bandwidth, global vs local coverage, best–effort) can be met by these different solutions. An integrated 5G-V2X and 5G-Uu chip, which is promised to become available, would drastically increase the coverage for short (and long) range services, as “all” connected devices would automatically support both channels.

This added value will have to prove itself. Some features are now only planned, and whether all possible functionality will be available is not just a technical question, but also a business case question. Stakeholders to include here are among others industry, public authorities and end users.

2 Introduction

2.1 Background

There is increased interest in the potential environmental benefits of Cellular Vehicle-to-Everything (C-V2X), given that substantial transport emissions reductions are required to help mitigate climate change. Following the EU Green Deal, the upcoming EC Strategy on Sustainable and Smart Mobility (Q4 2020) intends to propose matching measures to the “unprecedented ambition to achieve 90% reduction in emissions by 2050”. The question is to what extent connected driving, with increasing levels of automation, can lead to environmental benefits. 5GAA, the 5G Automotive Association, asked TNO to conduct a study into the environmental effects of V2X communication as it is currently used in transport and as it can be used in future implementations.

2.2 Goals of the study

The overall goal of the study is to identify the emission reduction potential of large-scale deployment of C-V2X -both LTE-V2X (Long-Term Evolution Vehicular to X) and 5G-V2X- including and beyond the first services (to be) deployed (the so-called day 1 services, see C-ITS Platform Final report, 2016).

This concerns the benefits of C-V2X deployment (both LTE-V2X and 5G-V2X direct and network-based communications) in terms of emission reduction by 2050 in Europe (and other world regions). The exhaust emissions to be considered by the study are CO_2, but also pollutant emissions such as NO_x. The goal is to:

- Identify the most promising use cases from an environmental perspective and their respective benefits taking into consideration:
    - Collateral environmental benefits resulting from improved road safety.
    - Improvements to overall traffic efficiency (including traffic flow management, optimized traffic signal operations).
- Discuss the impact of new mobility trends facilitated by enhanced connectivity enabled by LTE and 5G (e.g. multimodality, shared mobility, MaaS).
- Derive estimations of the incremental environmental impact of connected driving, e.g. LTE and 5G networks deployment and operation alongside the road network, MEC, datacenters, etc.
- Study benefits arising from enhanced connectivity independent of and in conjunction with the powertrain (considering the uptake of low and zero-emission vehicles vs. conventional engines but also EV enhanced connectivity needs e.g. for battery management).

The study builds on available documents such as the 5GAA assessment of C-V2X market penetration in-vehicles, infrastructure and with other road users e.g. VRUs (based on 5GAA internal survey findings and other available sources), and the timeline for the mass-deployment of basic and advanced use cases (as per 5GAA roadmap described in the White Paper on C-V2X Use Cases Volume II) leading to autonomous and automated driving.

2.3 Boundaries of the study and role of TNO

The focus of this study is on the environmental effects of road traffic applications that rely on communication technologies, and not on the specific type of communication technology that is used.

Geographical focus of the study is on Europe, the United States and Asia. The time horizon is 2050: the study looks at evidence from existing applications, but also considers promising use cases that may only be realized several decades from now but are based on connectivity of vehicles, the infrastructure and travelers/goods. A path for gradual introduction of these systems will be sketched, but impacts will only be estimated for a fixed moment in the future.

The use cases considered can be pre-trip and on-trip use cases. Most of the literature and existing applications focuses mostly on the on-trip ones, though. Other aspects rarely covered in literature are possible rebound effects (from improving traffic efficiency, e.g. latent/ induced demand) and how results scale up to the level of entire road and mobility networks; these aspects are discussed but they were not included in the impact assessment.

Only direct environmental impacts from traffic and transport are considered, not additional impacts related to e.g. energy use of back-offices or energy and resources needed for the production and operation of C-ITS systems. Also, out of scope for this study are: electrification of the powertrain, vehicle downsizing/resizing, CO_2 emissions as a result of manufacturing (less) vehicles, and the carbon footprint from 5G deployment.

Concerning the role of TNO: TNO is a public, independent, not-for-profit research institute, established by law. Hence, TNO's independence is founded very solidly, and is one of our most valuable assets. This is why we are a trusted partner of both Dutch, European and oversees governments, as well as a consulting and research & innovation partner to leading industry parties. In this independent role, TNO is a member of many associations, always with the aim to share and generate state-of-the-art knowledge and to be connected to relevant stakeholders in a particular field. If TNO's independence would be under pressure, we would immediately cancel our membership or participation. Specifically, pertaining to TNO's membership of 5GAA, TNO primarily serves as a knowledge partner on subjects related to 5G connectivity technology and architecture. Concluding, we fully ensure, confirm and insist on an independent role in this 5GAA project assignment.

2.4 Methodology

The methodology followed for this study aims at achieving the goals of this project, in the best way possible given the limited timeline.
A mix of supporting quantitative data and qualitative evidence on benefits associated with C-V2X establishes a basis for gaining the desired insights on promising use cases and conducting an impact analysis.
The specific elements of the current study approach are the following:

A. Literature research, which included looking for evidence of the reduction potential for various use cases in past projects and studies.

B. Identification of promising C-V2X use cases, in addition to those found in literature. This includes what we see as emerging mobility concepts using C-V2X services and ways in which connectivity can be used to address current inefficiencies of the transport system. Important input on this is provided also via interview sessions with 5GAA OEM-members and non-5GAA members.
C. Impact analysis. This includes both qualitative and quantitative analysis. The latter is performed also with TNO emission tool “EnViVer”, to further explore the potential of some of the promising use cases.
D. System level analysis, which includes the possible implementations with current and future communication technologies.
E. Conclusions and recommendations.

Given the short timeline of the study, the literature study was limited to a maximum number of studies (30 in the longlist, 10 in the shortlist for in-depth analysis) and the number of interviews was limited to 10. Accordingly, the impact analysis performed using the TNO tool EnViVer was limited in scope in terms of the use cases considered, the time horizon and the magnitude examined.
Thus, the overall approach is to examine and compare as far as possible results from existing projects, studies and implementations. This study does not produce new data.

Impact mechanisms
Several impact mechanisms have been considered in this study, in order to express how the reduction of emissions can be achieved. These impact mechanisms are related to several existing inefficiencies of the transport and traffic system, which appear either pre-trip or on-trip. In Table 1 the identified mechanisms are presented with a description of how these could be actualized.

Table 1: Impact mechanisms.

Reduction of trips	Avoidance of ‘unnecessary’ trips – this can be a personal and/or policy decision (e.g. working from home, combination of activities)
Reduction of kms driven and/or departure time shift	Improved route choice; Closer destination choice; Avoid travelling during peak hours; leading to improved driving patterns (avoiding congested traffic)
Modal shift	Improved mode choice (bicycle, Public Transport etc. instead of private car), e.g. by using new mobility services (ridesharing, MaaS)
Reduction of vehicle dynamics	Improved acceleration and deceleration patterns; Avoid unnecessary stops and idling; Avoid excessive braking; Optimal speed, acceleration and gear choice
Powertrain operation	(Compulsory or voluntary) shift to an electric mode in certain locations/situations where this has environmental benefits (for hybrid vehicles).

3 Literature research

3.1 Description of the process

The main purpose of the literature research part of the study is to identify state-of-the art projects, which studied possible environmental benefits of promising existing use cases of (C-)V2X.
We look at use cases that require communication to obtain information that is external to the vehicle. In the remainder of this report, we adopt the terminology regarding the possible types of vehicle communication as specified on 5GAA's official website[1]:

- Short-range direct communication: Vehicle-to-Vehicle (V2V), Vehicle-to-(Roadway) Infrastructure (V2I) and Vehicle-to-Pedestrian (V2P) using direct communication without necessarily relying on network infrastructure;
- Long-range network-based communication: Vehicle-to-Network (V2N) using traditional cellular infrastructure.

Different combinations of vehicular communication (e.g., V2N2I) are possible and are further elaborated in section 7.

The first step in the literature research was to make an overview of use cases, mentioned in several literature review studies and reports, and the identified associated environmental impacts. These use cases are mostly examining impacts emerging from the implementation of specific in-vehicle applications, using different types of communication technologies. This was achieved by performing a first screening process in the available literature, examining relevant keywords and results, which led to inclusion and exclusion of specific studies. It was necessary to add some other interesting publications to the existing list in the request for proposal, including studies from other world regions, as well as TNO studies and analyze the information in these publications. A set of around 30 studies was included in a longlist. This longlist was reduced to a shortlist of publications, which were examined in more detail. For these studies, we developed a template that enables quick scanning of available publications. It includes relevant information about the impact assessment: approach (real-world measurements, simulations, expert judgment, etc.), assessment of the reliability (whether or not the results are well explained and credible), scalability/transferability of results mentioned (were results found for very specific situations or can they be expected to occur elsewhere and/or in other situations?).

3.2 Longlist

The starting point for this literature search has been the review of several meta studies and reports with state-of-the-art applications in the area of communication technologies used in transportation, leading to environmental benefits. From those, references to specific cited projects and applications provided the basis for the selection of promising use cases. We further tried to identify areas and topics which seem promising, but for which not much research has been done or the range of application was limited, i.e. only simulation study, missing validation from real data. As TNO, we have been strongly involved in many, mostly European, but also Asian,

[1] 5GAA website: https://5gaa.org/5g-technology/c-v2x/

projects related to evaluation of connectivity technology used for improvements in the transport system, therefore, a big part of our study includes use cases originating from those.

The approach has been targeted to identify and review relevant studies and deployments, focusing on those producing quantitative data. The scope, as mentioned, is universal and data from anywhere that it is relevant, with solutions potentially transferable, have been considered. Eventually though, the majority of the final selected studies comes from Europe.

The full longlist of projects, reports, papers and online articles can be found in Appendix A, while details for the citation of these can be found in the section of references. Overall, various previous studies have investigated the CO_2 reduction or fuel savings potential of mostly (C-)ITS and CAD applications, while many others have considered other types of pollutants, such NO_x, PM etc. Studies include EU and US projects, national or local projects for public authorities, industry, research institutes, universities, etc. For these studies, some information has been extracted on which the selection for the shortlist could be based. The calculation and prediction of expected impacts are based on different approaches, including real data collection (field operational tests, deployments on diverse scales), modelling approaches, including extrapolated or scaled-up data, or even estimations coming from expert judgement and from state-of-the-art overview reports. Therefore, the data types and results, as well as their reliability, transferability and scalability can vary broadly. The literature we selected focuses on quantitative, validated data, rather than expert opinions. The assessment for the shortlist is based on promising results, adequate information on implementation and results of the use case, satisfactory approach, and the reliability of identified impacts. The reliability of identified impacts depends on different aspects. These aspects are:

- Method used (simulation vs on-road trials); scaling up or not in the latter case;
- Range of use case implementation (e.g. track test or full network);
- Impact on traffic or only vehicle level;
- Validity and sensibility of results;
- Assumptions and limitations of each study.

3.3 Shortlist

The final shortlist consists of ten reports and papers and can be seen in Table 2. The filled in templates for the shortlist can be found in Appendix B. These summary templates contain information regarding all use cases that are mentioned in the source, the region in which the impacts are described, the methodology and, where appropriate, remarks regarding the assessment of reliability, transferability, scalability and feasibility of the study. In these ten sources, different use cases and applications are mentioned. The reported results for these use cases are examined in this chapter in more detail. First, a short description of all the use cases/ applications is included. Then, further elaboration on and comparison of some aspects of the studies is presented, including the impacts found and the kind of methodology followed.

What needs to be noted is that most of the applications offering quantitative results found in literature are about on-trip services and less about pre-trip ones. They are mainly related to vehicle operations and in most of the studies simulation has been used to identify the impact of a full-scale implementation.

Table 2: Shortlist literature.

No	Use cases/applications	Source
1	**(Platooning) Vehicles platoon in a steady state, Continuous traffic flow via Green Lights Coordination, Group start, Speed Harmonization**	**C-V2X Use Cases Volume II: Examples and Service Level Requirements** 5GAA
2	**EcoSmart Driving** **Eco Freight & Logistics** **ecoTraffic Management & Control**	**Project eCoMove** ICT for Safety and Energy Efficiency in Mobility: Cooperative Mobility Systems and Services for Energy Efficiency 2010-2014
3	**Urban Traffic Control;** **Green Navigation;** **Eco-driving**	**Project ICT-EMISSIONS** Low carbon multi-modal mobility and freight transport: Development of a methodology and tool to evaluate the impact of ICT measures on road transport emissions 2011-2015
4	**V2V and V2I cooperative alert system**	**V2V and V2I Communications for Traffic Safety and CO_2 emission reduction: a performance evaluation** Outay et al. 2019
5	**Advanced driver assistance systems** (FCW, ACC, SRS, BLIS, LDW, IW, CSW, FEA, SafeHMI)	**Project euroFOT** **European Field Operational Test on active safety functions in vehicles** 2008-2012
6	**C-ITS** [**Traffic Signal Priority,** **Traffic information and smart routing**]	**Study on the deployment of C-ITS in Europe: Final Report**. Report for DG MOVE MOVE/C, 3, 2014-794.
7	**Eco-Signal Operations Applications;** **Eco-Lanes;** **Dynamic Low emission zones**	**AERIS** program US 2011-2014
8	**PCC (Predictive Cruise Control)**	**Predictive Cruise Control: Utilizing Upcoming Traffic Signal Information for Improving Fuel Economy and Reducing Trip Time** Asadi & Vahidi, 2010
9	**Heavy-duty truck platooning (ACC for leader, CACC for followers)**	**Influences on Energy Savings of Heavy Trucks Using Cooperative Adaptive Cruise Control** McAuliffe, B. et al., 2018
10	**CACC for lane closure** (V2X)	**Impact on Congestion and Fuel Consumption of a Cooperative Adaptive Cruise Control System with Lane-Level Position Estimation** Talavera et al., 2018

3.3.1 Description of use cases from literature

Below, a short description is provided for the applications used in each use case.

Eco-driving support systems:
Systems (including applications) which offer advice on speed, gear selection, acceleration, deceleration and other parameters such as parameters regarding car-following and lane change, which can contribute to energy/fuel efficient or low emission driving behavior. Example applications: ecoAssist, ecoDriving support.

Green navigation:
Real-time in-vehicle navigation. Routing recommendations based on calculation of environmental impact and real-time traffic situation.

Traffic information and smart routing (SmartR)
The provision of traffic information and smart routing services to vehicles, intended to improve traffic efficiency and aid traffic flow management.

Urban Traffic Control (UTC):
Influences traffic flows allowing reduction of fuel consumption and CO_2 emissions, by synchronizing and optimizing traffic lights along urban axes.

Traffic signal priority (TSP):
The traffic signal priority request by designated vehicles allows drivers of priority vehicles (for example emergency vehicles, public transport, HGVs) to be given priority at signalized junctions.

Eco-Signal Operations:
Uses connected vehicle technologies to decrease fuel consumption and emissions at signalized intersections. Priority can be given to all vehicles, freight vehicles and transit vehicles. Multiple applications: Eco-Approach and Departure at Signalized Intersections, Eco-Traffic Signal Timing, Eco-Traffic Signal Priority (Freight and Transit), Connected Eco-Driving.

Eco-Lanes:
Dedicated freeway lanes – similar to managed lanes – optimized for the environment that encourage use of vehicles operating in ecofriendly ways. Applications: Eco-Speed Harmonization, Eco-CACC, Eco-Ramp metering, Connected Eco-Driving, Eco-Traveler Information Applications.

Dynamic Low emission zones:
Geographically defined areas that seek to incentivize “green transportation choices” or restrict high-polluting vehicles from entering the zone. Applications: Connected Eco-Driving, Dynamic Emissions Pricing, Electronic Toll Collection (ETC), Multi-Modal Traveler Information.

ecoBalanced Priority:
Adaptive traffic light control, optimizing the control based on stationary sensor data. Within eCoMove equipped trucks can request priority by V2I Communication. This is possible on the main route passing all four intersections in both directions.

ecoGreen Wave:
Dynamic green wave via traffic light controllers' synchronization. Optimizing the driver behavior to reduce fuel consumption.

Alert systems:
Technologies to alert motorists when they approach a hazardous zone, such as low visibility area, and recommend proper speeds. Reduces the need for braking, accelerating and unnecessary stops, therefore reducing fuel consumption.

Cooperative Adaptive Cruise Control (CACC) for lane closure:
In case of CACC, information is shared among vehicles in a platoon aiming at a harmonized cruising speed. In the application mentioned in this study, CACC solution is proposed that only uses communication to make its decisions with the help of previous road mapping. In the study, CACC is used to smoothen traffic flow in approaching a lane closure.

Heavy-duty truck platooning (ACC for leader, CACC for followers):
Truck platooning refers to a group (two or more) lorries, using connectivity technology and automated driving support systems, to drive safely in convoy, a short distance apart. In this specific application, the first truck was always in ACC mode, and the followers were in CACC mode using wireless V2V communication to augment their radar sensor data to enable safe and accurate vehicle following at short gaps.

ecoApproach Advice:
Infra-based speed advisory using vehicle data (CAM) stationary sensor data and traffic light signal information. Speed advice reduces the need for acceleration and deceleration, thereby reducing fuel consumption.

Predictive Cruise Control:
The use of upcoming traffic signal information within the vehicle's adaptive cruise control system to reduce idle time at stop lights and fuel consumption.

ecoRamp metering:
Traffic management application to maintain the benefits of (traditional) ramp metering for the mainline and at the same time minimize the negative side effects at the on-ramp. It does so by minimizing start-stop waves through a virtual stop line and distinguishing between high emitting and low emitting vehicles.

Fuel efficiency advisor (FEA):
The FEA supports the driver in maintaining the engine speed in the "green area" towards optimal usage of the vehicle with respect to fuel efficiency.

3.3.2 Classification per use case
Table 3 shows the classification of each of the applications with respect to the level on which the application acts. Three levels have been identified and used throughout the current study: the vehicle, the traffic and the system level. Applications related to the operational level of driving and which mostly affect the vehicle dynamics, belong to the vehicle level. Others, which affect the overall traffic flow and network and are more related to the tactical level of driving, correspond to the traffic level. The system level pertains mostly to cases where strategic decisions of road users are influenced, e.g. the route choice.

Table 3: Impact level of each application.

	Level on which application acts		
Application	**System**	**Traffic**	**Vehicle**
ecoSmartDriving			X
ecoTrafficManagement & Control		X	X
Urban Traffic Control		X	
Green navigation	X		
V2V/V2I Alert systems		X	X
FEA: Fuel efficiency advisor			X
Traffic signal priority (TSP)		X	
Traffic information and smart routing (SmartR)		X	
Eco-Signal Operations		X	X
Eco-Lanes		X	X
Dynamic Low emissions zones			
Predictive Cruise Control		X	X
Heavy-duty truck platooning (ACC for leader, CACC for followers)		X	X
CACC for lane closure		X	X

3.3.3 Reported impacts per use case

In Table 4, all the applications from the reviewed literature are listed. For each application, it is shown whether the results are based on simulation models/ driving simulator or on real-world pilots/trials. This affects the validity of the data used, whether it came from a field study with real vehicles or an algorithm implemented in simulated vehicles. Furthermore, the table shows whether the measured results are described for the traffic level (full network under investigation) or just for the individual vehicles that use the application. Then, the impacts found are listed, with respect to fuel, CO_2 and NO_x reduction. Sometimes this is presented as an average value, but it can also be a range, depending on penetration rates of the application, or the road network it has been tested in. This gives an indication of the potential of the application.

Table 4: Method, impact level and measured impact per application from literature.

	Method		Level on which impact is described		Average/ range of reduction in specific use case		
Application	**Simulation models/ Driving simulator**	**Pilot/ trials**	**Traffic**	**Individual Vehicle**	**Fuel**	**CO_2**	**NOx**
ecoSmartDriving		X		X	4.5% - 18.6%		
ecoTrafficManagement & Control		X	X	X	3.6% - 17%		
Urban Traffic Control	X		X			1.7 - 4.8%	
Green navigation	X		X			1.1 - 9.5 %	

V2V/V2I Alert systems	X		X			5%	
FEA: Fuel efficiency advisor		X		X	1.9%		
Traffic signal priority (TSP)	X		X		8.3%	8.3%	8%
Traffic information and smart routing (SmartR)	X		X		1.95%	1.95%	
Eco-Signal Operations	X		X		1 - 13%		0.5 - 20.2%
Eco-Lanes	X		X		4.5 - 22%		
Dynamic Low emissions zones	X		X		2.5 - 4.5%		
Predictive Cruise Control	X			X	47%	36%	
Heavy-duty truck platooning (ACC for leader, CACC for followers)		X		X	6 - 17%		
CACC for lane closure	X	X	X		15 - 33%		

Figure 2 and Figure 3 are visualizations of these impacts. The figures show CO_2 reduction, but where no CO_2 reduction was listed in the studies, it is assumed that the fuel reduction is equivalent[2]. The two figures show the same impacts; however, they are categorized differently. Figure 2 uses a classification of the applications per method used, making the distinction between pilots or field trials, and simulation models or driving simulator tests. Figure 3 describes the applications and distinguishes the level on which the impact is described, which can be vehicle or traffic level. For vehicle level, the impacts are only described for the equipped vehicles, whereas for the traffic level, a penetration rate is considered and the effect on the whole traffic network under investigation, for this specific study, (equipped and non-equipped vehicles) is described.

It is clear from these different distinctions, that impact may be described in many ways, and that direct comparison between use cases is not only difficult but also not recommended. Not only are the implementations of the applications different (e.g. different penetration rates are tested), also the scenarios assumed, region of implementation and type of roads studied vary. Sometimes the study considers only limited traffic situations or different congestion levels. The effects also differ when a single corridor (coordinated or uncoordinated), or even a single vehicle, is considered as compared to a whole network. Furthermore, the improvement in CO_2 reduction is compared to a base scenario, but this base scenario may also vary in different studies, which makes it challenging to assess the real added value of communication. What should be noted at this point is the fact that in the future, this base scenario will also differ considering the current traffic composition and the expected higher adoption rate of “cleaner” (hybrid or fully electric) vehicles. Thus, both the absolute and the relative impacts will change. In fact, if in 2050 all vehicles are zero-emissions vehicles, using renewable energy, the only effect that will still be there is reduced

[2] In the future, with higher shares of EVs, this may no longer be the best assumption.

demand for sustainably produced energy, via the energy use per km and via km's not driven. Details and specifics of the implementation thus influence the described impacts, and therefore one must be careful when comparing the results.

It can be seen that the impacts found in studies using pilots (Figure 2) are typically higher than for simulation models. This corresponds with the fact that most studies that use pilots examine effects on a vehicle level. This means that the effect of the application on traffic other than the equipped vehicles is not (yet) considered. It is thus important to note that the effect may be different when it is described on a traffic level.

The described effects for two studies are much higher than for the others, this is the case for Predictive Cruise Control (PCC) in Asadi & Vahidi, 2010, and CACC for lane closure (Talavera et al., 2018). It must be noted that these studies describe impacts in a confined situation. For PCC, the study looks at a single corridor with traffic lights. The PCC is used to minimize the braking for traffic lights. The described effect (36% reduction of CO_2 emissions) is, thus, only for this corridor. The effect in other road sections and road types is not described. Additionally, the effects are described only on a vehicle level. In the case of the second CACC study mentioned, the simulation was performed for a single corridor as well, where CACC is used for traffic smoothing when approaching a lane closure on an interurban road. Also, in this case, effects for other road sections and road types may be lower.

For some applications, the range of impacts is quite large, sometimes more than 10%-point difference between the lowest and highest described impact. The range is based on variations in different variables and parameters. For instance, in eCoMove, the range depends on the specific use of the applications. For CACC, it depends on the traffic demand in the simulation, which is high or low. In the applications of AERIS, it depends on the penetration rate, the traffic volume assumed, offer of incentives, type of vehicles that are given priority, as well as whether more services were combined.

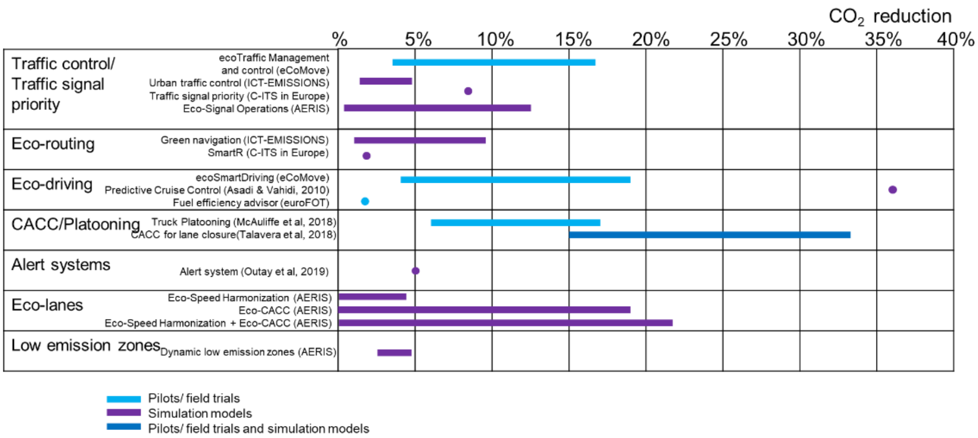

Figure 2: Impacts of different applications classified per method

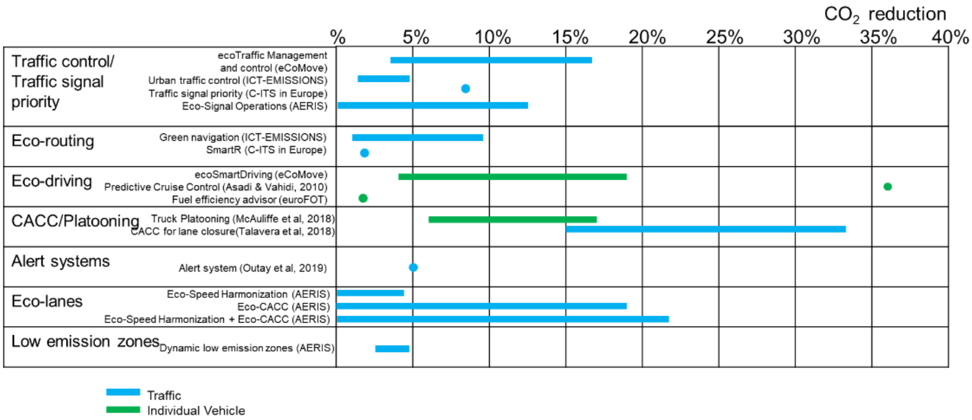

Figure 3: Impacts of different applications classified per level on which the impact is described

4 Interviews

4.1 Purpose of the interviews

The main purpose of the interviews pertains to the collection of extra information and reference sources, deriving directly from experts in the field of connectivity and communication technologies.

Interviewees were asked which promising use cases (services, specific applications, etc.), using connectivity in traffic (V2V, V2I, V2N), they foresee and how these are expected to result in environmental benefits. Our time horizon has been indicated to be up to 2050, thus, thinking beyond the current possibilities while sharing thoughts, has been certainly encouraged. Additionally, it was asked according to which mechanisms these use cases would have an impact on emissions and how large the expected impact would be.

Findings from the previous steps were shared with the interviewees to explore other potential use cases. Results were merged with the results from the previous step in order to complete the overview of promising use cases and expected environmental impacts. The results were also input for the system levels analyses.

4.2 List of interviewees

The interviewees cover a wide range of backgrounds, as they are selected from diverse markets and industries, geographical areas and different expertise. Thus, there is a good spread over OEMs, road authorities, traffic experts, consultants, industry and academia.

In total, ten on-line interviews were carried out, using videoconferencing. In Table 5, the overview of the interviewees is presented, by the name of their organization.

Table 5: List of interviewees' organization

Robert Bosch GmbH (Mobility Solutions)
European Automobile Manufacturers' Association (ACEA)
BMW Group
Delft University of Technology (department Transport & Planning)
Bishop Consulting
ERTICO – ITS Europe
Federal Highway Research Institute (BASt)
Agora Verkehrswende (Environmental consultant)
Tongji University (College of Transportation Engineering)
Finnish Transport and Communications Agency (Traficom)

4.3 General outcomes

Overall, the interviews facilitated the current study in two ways. Firstly, by providing feedback to the interviewers on the extent to which they are on the correct path, in terms of the use cases already identified as promising ones. Secondly, by providing different perspectives on the future vision for the transport system and the expected changes.

What has been widely noted is that the interviewees had difficulty in framing a concrete picture of how 2050 will look like for the transport and traffic system and what can be expected as potential for C-V2X technologies regarding environmental impacts. However, there were some clear views that if people do not accept some risks, there will be no way forward and, as indicated by one of the interviewees, this is something that has been noted with many (dubious) examples in the past that are now a reality (in the introduction of ADAS for example). What has also been expressed is that, even though the exact role of the communication technologies, with respect to environmental impacts, is not yet identified, it is certainly valid to say that the sooner we have more direct, better and faster communication, which will enable more coordination and cooperation, the better. In the near term, it is rather limited what we can do in terms of emissions, but if we move to higher levels of automation, resulting in smoother traffic flow (assuming the same km driven), then we can expect much higher energy and emission benefits. In the same line, discussions were raised around the deployment strategies to be followed. While some interviewees mentioned a step-by-step approach, with respect to the road network and vehicle types to put first focus on, some others mentioned that there is no real emphasis and no better or worse use case, since everything should and will be controlled sooner or later.

Another point raised was the potential emergence of electrification, as well as vehicle downsizing and resizing, which will have much bigger impacts on emissions than communication technologies. This is a valid point to be accounted for future impacts, however, remains out of scope for this study. In relation to more system level changes, every single interviewee referred to the fact that as planners, we should put focus on affecting also the travel behavior, aiming at reduction of trips, modal shift (public transport still seen as the most efficient solution) or better management of the vehicle capacity, e.g. by shared mobility concepts. There were references to concepts such as Mobility-as-a-Service (MaaS) but also Logistics-as-a-Service (LaaS). This is seen as the biggest challenge but also as a huge opportunity for communication technologies to contribute to the simplification and better development of such concepts via seamless and ubiquitous long-range communication.

Several enablers for communication technologies were also mentioned (e.g. edge computing, big data management and data analysis). Overall, few interesting new use cases – other than the ones already identified in the literature – came up from the discussions and it seems that most of high hopes rely on “everything connected to everything” but, as mentioned, there is still no clear view of the long-term future.

4.4 Use cases derived from interviews

As an indication of the different use cases mentioned during the interviews, we provide the following list:

- Smart intersections/ traffic lights coordination.
- Eco-routing advice and congestion recognition.
- Eco-driving advice.
- Speed guidance and speed limitation warning.

- Parking guidance and advice. It can provide searching time savings for vehicles so that traffic is alleviated and less emissions can be achieved.
- Dynamic cooperative traffic flow.
- Cooperative maneuvering (e.g. lane changes).
- Automatic switches (hybrid to electric) in certain locations, to reduce fuel consumption (requires a plug-in hybrid and knowledge on whether the electricity used is from a renewable energy source).
- Bike connected to everything (B2X). 'Smart' electric bikes could use communication technologies to exchange information with other vehicles and traffic lights, so that riding becomes smoother and green waves for bikes can be achieved. This becomes promising mostly when car trips are replaced by smart bikes and not for normal bike trips.
- Automated driving. Especially from level 4 up, communication technologies are necessary to achieve the highest expected benefits.
- Connected vehicles for flexible road use, such as (bus) lanes that can be used to form an extra lane in peak hours.
- Platooning. This can be related to either truck or passenger vehicles platooning.
- CACC.
- Dynamic pricing. It can determine fees and incentives using data collected from vehicles and the environment (e.g. real-time emissions and air quality data, excessive speeding, weather conditions, traffic, etc.). Dynamic geo-fencing could be further enabled to adjust boundaries of the tolled area based on various criteria.
- Traffic signal priority for both trucks and passenger vehicles.
- Intelligent merging. Inter-vehicle communication and road-vehicle communication mechanisms can contribute to a safe and smooth merging operation in automated vehicle systems.
- "Everything connected to everything". This last special use case has been defined and formulated in more detail in the following section of this report.

5 Promising use cases

5.1 Selection of promising use cases

The selection of use cases presented in this chapter is considered ‘promising’, in the sense that they have the potential to reduce a substantial amount of emissions, enabled by communication technology.

The list of selected promising use cases is based on the short list of the literature review, input from the interviewees, TNOs experience and ideas based on earlier projects executed.

Understanding the mobility system gives insights into potential future use cases that can contribute to environmental goals. The mechanisms by which this reduction is achieved, can be very different. For example, the driving pattern can be made ‘smoother’ by applying CACC technology, while also kilometers can be reduced by applications like dynamic ride sharing. Another case can be an application that reduces the risk of accidents and thereby accident-related congestion (see e.g. Outay et al., 2019 for an application on traffic safety and CO_2 emission reduction). The focus in this study is on applications that can reduce emissions while already driving. However, avoiding kilometers (or complete trips) is also a very efficient mechanism to reduce emissions, therefore, use cases that reduce emissions by this mechanism are also presented.

In this chapter, in order to give more insight into the reason why these use cases are considered as promising and how the emission reduction can be achieved, the use cases are assigned to different impact mechanisms. Furthermore, the promising use cases act on different levels in the traffic system. The use cases are, thus, clustered by different impact levels, in order to create more insight into the operational details and effects of the selected use cases.

The list with promising use cases, resulting from the literature review, interviews and our own expertise, is the following:

- Automated intersection crossing
- Bike-to-everything
- CACC
- Continuous Traffic Flow via Green Lights Coordination
- Continuous Traffic Flow via Green Lights Coordination (priority request for high emitters)
- Cooperative Lane Merge
- Dynamic Geofencing
- Dynamic pricing
- Dynamic ride sharing
- Eco-trip planning
- En-route/ on-trip (eco-driving) advice
- “Everything connected to everything” *
- Flexible road use (e.g. Dynamic tidal flow lanes)
- Group Start
- Location-based automatic switches hybrid to electric
- On-street parking service

- Real-time optimal route advice
- Shared mobility route planning
- Shockwave damping
- Speed Harmonization
- Traffic Jam Warning and Route Information
- Vehicles Platoon in Steady State

N.B. Names of the use cases have been aligned with the terminology used by 5GAA.

*One special use case with high potential has been added, namely “Everything connected to everything”, which has also been mentioned by several of the interviewed people as the most promising use case in the (distant) future. This is a holistic concept, referring to the possibilities which will become feasible if all road users are connected to each other and are able to share real-time information (like position, speed, acceleration but also intentions). It will offer on all levels (vehicle, traffic and system) all kind of possibilities (extending the possibilities of some of the use cases already mentioned in the table). The information of all connected objects can be used to optimize the traffic flow in the most advanced way. For example, all approaches to intersections can be coordinated so that no one has to stop. It is thus assumed that virtually the whole trip can be made more efficient (in terms of energy use and emissions, at least).

5.2 Clustering of use cases against traffic level

There is a variety of possible ways to cluster and categorize the use cases examined for this study. We choose as clustering criteria the level at which communication technologies can be used to achieve positive environmental impacts at the system, the traffic and the vehicle level. By ‘system’ level, we refer to the overall mobility system in which people choose (or not) to move, and the rest of the different choices they need to make, such as route and departure time choice. By ‘traffic’ level, we refer to the traffic flow, the traffic volume and demand, the road level of service, traffic management and in general the environment where a vehicle is moving. By ‘vehicle’ level, we refer to the functionalities of the vehicle itself and its characteristics while moving, such as speed, kilometers travelled etc.

The use cases can then be clustered accordingly. If a use case has effects on different levels, the level has been chosen for which the use case has its primary aim. For example, "Continuous Traffic Flow via Green Lights Coordination" influences the vehicle level, but it aims to improve the total traffic flow instead of only the vehicle equipped with the application.

Presented below are three different clustering matrices. The first overview presents the clustered use cases that were retrieved based on the different applications found in literature. The second overview presents the use cases that were discussed during the interviews. The third clustering matrix shows some additional use cases that were added by TNO to fill some of the gaps that were observed. The fourth clustering matrix is a combination of the use cases of the previous three, i.e. literature, interviews and additional cases by TNO. In this final matrix, some similar use cases are merged into one use case.

Before presenting the clustering of the identified use cases, Table 6 shows the relation between the use cases and the specific applications tested in literature. As can be seen in this table, use cases can be represented by one specific or a combination of several applications. This clarifies why certain use cases are assigned to several categories in the following tables and helps to understand the impact of the complete use case.

Table 6: Relation between use cases and applications from literature.

Applications / ***Use cases***	ecoBalanced Priority	ecoDrivingSupport	eco-driving HMI	ecoAssist	eco-driving HMI+haptic pedal	ecoApproach Advice	ecoGreen Wave	ecoRamp metering	Urban Traffic Control	Green navigation	V2V/V2I Alert systems	FEA: Fuel efficiency advisor	SRS: Speed regulation system	Traffic signal priority (TSP)	Traffic information and smart routing (SmartR)	Eco-Signal Operations	Eco-Lanes (Eco-Speed Harmonization, Eco-CACC)	Dynamic Low emissions zones	Predictive Cruise Control	Heavy-duty truck platooning (ACC for leader, CACC for followers)	CACC for lane closure
Eco-trip planning										x								x			
Real-time optimal route advice										x											
En-route/ on-trip (eco-driving) advice		x	x	x	x							x	x					x	x		
Dynamic Geofencing																		x			
Traffic Jam Warning and Route Information	x														x	x					
Continuous Traffic Flow via Green Lights Coordination	x						x		x					x		x					
Continuous Traffic Flow via Green Lights Coordination (priority request for high emitters)	x						x									x					
Cooperative Lane Merge								x													
Speed Harmonization					x						x		x				x		x		
Cooperative Driving Maneuver		x	x	x	x	x											x		x	x	x
CACC																				x	x
Vehicles Platoon in Steady State																				x	x

What follows in Table 7 is the clustering based on the impact level of each use case.

Table 7: Clustered use cases from literature

Level	**Use cases**
System	Dynamic Geofencing; Eco-trip planning; Real-time optimal route advice
Traffic	Continuous Traffic Flow via Green Lights Coordination; Speed Harmonization; Traffic Jam Warning and Route Information;
Vehicle	Cooperative Lane Merge; Cooperative Driving Maneuver; En-route/ on-trip (eco-driving) advice; Continuous Traffic Flow via Green Lights Coordination (priority request for high emitters); CACC; Vehicles Platoon in Steady State;

Next, the same format is used to show the use cases identified during the interviews, clustered in the same way, in Table 8.

Table 8: Clustered use cases from interviews

Level	**Use cases**

System	Dynamic Geofencing; Dynamic pricing; Dynamic ride sharing; Eco-trip planning; “Everything connected to everything” Real-time optimal route advice;
Traffic	Continuous Traffic Flow via Green Lights Coordination; Cooperative Driving Maneuver; Cooperative Lane Merge; “Everything connected to everything”; Speed Harmonization; Traffic Jam Warning and Route Information;
Vehicle	Automated intersection crossing; Bike-to-everything; Cooperative Driving Maneuver; Cooperative Lane Merge; En-route/ on-trip (eco-driving) advice; “Everything connected to everything”; Flexible road use (e.g. Dynamic tidal flow lanes); Continuous Traffic Flow via Green Lights Coordination (priority request for high emitters); Location-based automatic switches hybrid to electric; On-street parking service; CACC; Vehicles Platoon in Steady State;

Following, Table 9 presents all the promising use cases identified in both literature and interviews and also complemented by the authors’ view on further potential use cases, such as shockwave damping and shared mobility route planning.

Table 9: Clustered use cases from literature, interviews and TNO view

Level	**Use cases**
System	Dynamic Geofencing; Dynamic pricing; Dynamic ride sharing; Eco-trip planning; “Everything connected to everything” Real-time optimal route advice; Shared mobility route planning;
Traffic	Continuous Traffic Flow via Green Lights Coordination; Cooperative Lane Merge; Coordinated, Cooperative Driving; “Everything connected to everything”; Speed Harmonization; Shockwave damping; Traffic Jam Warning and Route Information;
Vehicle	Automated intersection crossing; Bike-to-everything; Cooperative Lane Merge;

	Cooperative Driving Maneuver; Flexible road use (e.g. Dynamic tidal flow lanes); En-route/ on-trip (eco-driving) advice; “Everything connected to everything”; Continuous Traffic Flow via Green Lights Coordination (priority request for high emitters); Group Start; Location-based automatic switches hybrid to electric; On-street parking service; Vehicles Platoon in Steady State;

What is interesting to note in this last table, is that the majority of use cases falls into the vehicle level. As already mentioned, most of the potential is currently explored and identified in ‘on-trip’ applications, with a focus on reducing vehicle dynamics, therefore this is a reasonable outcome. Some use cases, such as the Cooperative Driving Maneuver, belong to more than one level. The use case “Everything connected to everything” is found on all levels, since it is a combination of all promising use cases.

On the system level, we find use cases that change the mobility behavior concerning route choice, mode choice or reducing trips. As explained before, this last category is not considered for further evaluation in this study, however, the following example illustrates which impact can be achieved by modal shift, see Figure 4. Every avoided trip means a reduction of 100%. By a shift from going to work by hybrid car to going to work by (for example) a local train, 84% of emission reduction can be achieved.

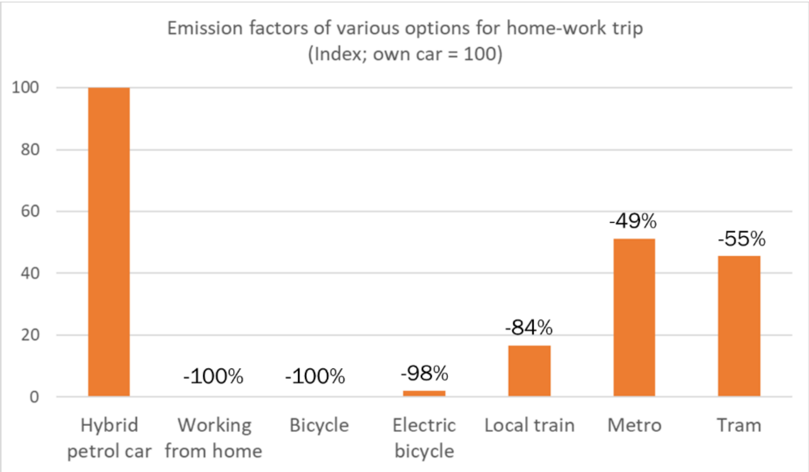

Figure 4: Emission factors of various options for home-work trip, as compared to the emission factor of hybrid cars (emission factors for the Netherlands, source of emission factors for different modes: https://www.co2emissiefactoren.nl/lijst-emissiefactoren/)

5.3 Impact mechanisms for the promising use cases

An interesting classification of the promising use cases is in relation to the identified impact mechanisms, i.e. how emissions are reduced. Reductions can be a result of improved driving patterns, such as reduced vehicle dynamics, improved route and departure time choice, modal shift, avoided trips and powertrain operation.
Table 10 below presents this categorization.

Table 10: Use case categorization based on different impact mechanisms.

Impact mechanisms / ***Use cases***	**Reduction of trips**	**Reduction of kms driven and/or departure time shift**	**Modal shift**	**Reduction of vehicle dynamics**	**Powertrain operation**
"Everything connected to everything"		x	x	x	
Automated Intersection crossing				x	
Bike-to-everything			x	x	
Flexible road use (e.g. Dynamic tidal flow lanes)				x	
Continuous Traffic Flow via Green Lights Coordination				x	
Continuous Traffic Flow via Green Lights Coordination (priority request for high emitters)				x	
Cooperative Lane Merge				x	
Cooperative Driving Maneuver				x	
Dynamic Geofencing	x		x		
Dynamic pricing	x	x			
Dynamic ride sharing		x			
Eco-trip planning		x		x	
En-route/ on-trip (eco-driving) advice				x	
Group Start				x	
Location-based automatic switches hybrid to electric					x
On-street parking service		x			
Real-time optimal route advice		x		x	
Shared mobility route planning		x	x		
Shockwave damping				x	
Speed Harmonization				x	
Traffic Jam Warning and Route Information		x		x	
CACC				x	
Vehicles Platoon in Steady State				x	

As can be viewed from the table, the most frequent impact mechanism mentioned for the use cases included is reduction of in-vehicle dynamics.

Some further possible clustering criteria can be related to the vehicles for which the application is developed (e.g. freight transport vs passenger cars), to whether the application includes long or short range communication and also to the time horizon of implementation of the use case (shorter or longer term – up to 2050). However, such clustering has not been implemented in this report.

6 Indicative impact analysis

In chapter 3, impacts of different use cases as found in the literature have been described. In addition to this, for important use cases for which no reliable impact estimates were available, an additional impact assessment has been performed. This will be presented in this chapter.

6.1 Selection of use cases for impact assessment

In this paragraph it is explained which use cases have been selected as topic for the indicative simulations, and according to which criteria.

The impact mechanisms explained in the previous chapter describe how emission reductions can be achieved for the different use cases. These can be summarized into two main categories: reducing the number of (car and truck) kilometers driven, and homogenizing or smoothening of speed profiles (or reduction of in-vehicle dynamics). Furthermore, some of the use cases are aimed at urban areas, such as (controlled) intersections, while others are mostly effective on corridors (rural roads or motorways). For the quantitative impact assessment study, only use cases with the impact mechanism of homogenizing speed profiles are selected, since the impact of this mechanism can be calculated with the emission tool EnViVer, as will be explained later.

N.B.: Improvement of traffic flow may lead to an undesirable rebound effect in the form of an increase of the total amount of traffic. This effect is not considered in the indicative impact assessment. The order of magnitude of such rebound effects is not known, and it is seldom discussed (neither in a qualitative or in quantitative way) in literature.

An indicative impact assessment with emission simulations will be done for use cases with a high expected potential, especially when no (credible) results from existing studies are already available.

The following 4 use cases represent a large part of the earlier presented promising use cases with the reduction mechanism of homogenizing traffic flow, and are therefore selected as the basic use cases for the impact assessment:

1. CACC
2. Eco-driving on motorways
    a. if congestion can be avoided;
    b. if regular driving patterns are smoothened.
3. Intelligent intersections
4. “Everything connected to everything”: the potential of all use cases aimed at smoothening the driving pattern.

6.2 Data

Different types of data sources have been used for the impact assessment, namely pilot data, real-world data, data from microsimulations and synthetic data. All of them contain trajectory data with sufficient resolution for the emission tool EnViVer (at least 1 Hz). The specific data sources will be explained below.

For the use case about CACC, data collected in a real-world pilot are used. In this pilot, platoons of 3 and 7 vehicles (Toyota Prius) equipped with CACC and data logging systems drove in regular traffic on a 2 lane rural road with controlled intersections (varying speed limits of 100-80-50 km/h), in the province of North-Holland in the Netherlands (N205). The trajectory was about 10 kilometers long. The pilot lasted 4 days, both in peak and off-peak hours. The days were divided in sessions of around 20 minutes in which the vehicles drove with a certain setting (with or without ACC/CACC). The following time of the CACC system was set to 0.6 seconds with additional 5 meters (for safety), which in practice is a little bit shorter than the average following time of human drivers (usually between 0.8-1.2 seconds). The following settings were included in the pilot: reference case (without using any system), reference case with information about the time to green, ACC with information about time to green, CACC with information about time to green and CACC with information about time to green and extended green time when the platoon approached the intelligent intersections. In order to determine the added value of direct communication between vehicles, we compared the cases with CACC (with information about time to green) with ACC (with information about time to green). The added value of the communication with the traffic light is therefore not analyzed in this specific example, this traffic light information is available in both situations.

For the use case about driving on motorways and avoiding congestion, a data set with simulated vehicle trajectories (from VISSIM) on a Dutch motorway (A50) was used. The data set contains simulated trajectory data calibrated with real traffic data during two 1h20m periods on two different days, one with congestion caused by an accident and one without, same time of day and with similar traffic intensities. This case represents the impact that can be achieved by using communication to avoid congestion, such as with Traffic Jam Warning and Route Information systems, en-route/ on-trip (eco-driving) advice, shockwave damping systems, or safety systems that can prevent accidents.
To furthermore estimate the potential of systems that can smoothen the driving pattern, synthetic speed profiles were created with smoothed dynamics on roads with different speed limits.

For the use case about intelligent intersections, two different sources have been used. The first source contains measured emission data from trucks passing an intersection, collected within the Catalyst program[3]. The data was collected from 5 instrumented (DAF) trucks during 25 weeks of driving. Trajectories driven by the equipped trucks on provincial roads were selected when they crossed a (controlled) intersections (intelligent or not) were selected over two kilometers around each intersection (1 kilometer approaching the intersection and 1 kilometer after the intersection; only when the truck did not have to slow down for other intersections

[3] The CATALYST Living Lab is a public-private partnership (PPP) jointly setup by the Ministry of Infrastructure and Water Management, Topsector Logistiek/TKI Dinalog, NWO and SIA. Over 40 parties work together in the CATALYST Living Lab to “develop and accelerate Connected Automated Transport innovations for safer, more efficient and sustainable heavy road transport”

within these 2 kilometers). This resulted in a selection of 902 trajectories, including trajectories where vehicles did not have stop, or came to a partial or complete stop. Furthermore, to further estimate the potential of intelligent intersections, synthetic trajectory data were constructed with and without stopping for the intersection. This illustrates the potential of communication systems that can avoid vehicles to stop at intersections. N.B. the impact on other traffic, which can be both negative and positive, was not considered.

Combining the estimated impacts of all these data sets will illustrate the potential for the use case "everything connected to everything".

6.3 Vehicle emissions assessment tool EnViVer

TNO's emission assessment tool "EnViVer" originates from '**En**vironment, **VI**SSIM (traffic microsimulation) and **VER**SIT+ (vehicle emission simulation). Using this tool, the emission impacts of changing driving behavior can be explored, illustrating the potential of promising use cases aiming for environmental benefits. Key characteristics of EnViVer are:

- It simulates traffic emissions CO_2, NO_x and PM10, for single vehicles as well as for thousands of vehicles.
- It does that realistically and with high temporal and spatial resolution, i.e. 1 Hz and e.g. <=25 m (up to 90 km/h).
- It is based on TNO VERSIT+ vehicle emission models for 400+ detailed vehicle classes (Dutch fleet).
- It uses 'average' vehicle emission models for seven vehicle classes, e.g. car, van, truck, bus for two fleet compositions (Dutch city roads resp. motorways).
- Licensed to authorities and companies in 35+ countries and to 50+ universities.
- Possible inputs to EnViVer are:
    - VISSIM traffic microsimulation data simulating vehicles in a traffic network.
    - Real world measured vehicle data, e.g. vehicle speed and emissions.
    - Minimally required input: vehicle speed (@ 1 Hz) per vehicle.

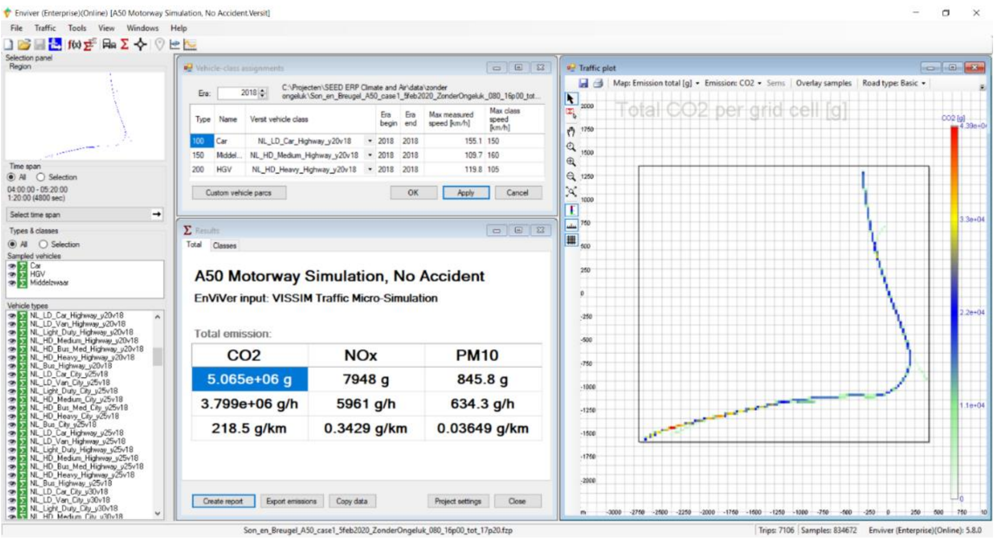

Figure 5: Screenshot of EnViVer user interface.

6.4 Model settings as used for the EnViVer example use-case-calculations

In the use cases for which EnViVer emission calculations were performed, i.e.

1. CACC: CACC pilot study (paragraph 6.5.1)
2. Eco-driving on motorways: Motorway simulation without and with accident (paragraph 6.5.2), and emission reductions of smoothed speed dynamics from simulated speed profiles (paragraph 6.5.5)
3. Intelligent intersections: Emission reductions when avoiding stops from measured truck data (paragraph 6.5.3), and from simulated speed profiles (paragraph 6.5.4)

The following EnViVer setting choices were made:

- All simulations were done with emission factors for the Dutch fleet in 2020.
- Most simulations were performed with the Dutch fleet composition as on motorways. For checking purposes, some were done with the city composition and though these gave as expected slightly different results in absolute sense, the relative results were similar.
- The multiple vehicles simulations, for a motorway (paragraph 6.5.2), were performed with the EnViVer vehicle emission models for the average Dutch passenger car and the average Dutch medium and heavy weight trucks.
- All single vehicle simulations, with measured (paragraph 6.5.1) or simulated (paragraph 6.5.4 & paragraph 6.5.5) speed profiles, were performed with the EnViVer vehicle emission model for the average Dutch passenger car.

6.5 Results

6.5.1 Pilot with CACC on Dutch rural roads

For the impact assessment of CACC on Dutch rural roads, we used the data from the real world pilot as described in paragraph 6.2. These data were clustered into 7 sets of 2 trips on the same day and within the same period of the day. In each set of trips, one trip was driven with ACC and the other trip with CACC, in a platoon of either 3 or 7 vehicles. The trajectories of the middle vehicle were used for the emission calculation and comparison.

The average CO_2 emission reduction by using CACC (with V2V communication) compared to ACC (without V2V communication) in this pilot is calculated at 6.0%. This percentage varied quite a lot per trip, as can be seen in Figure 6.

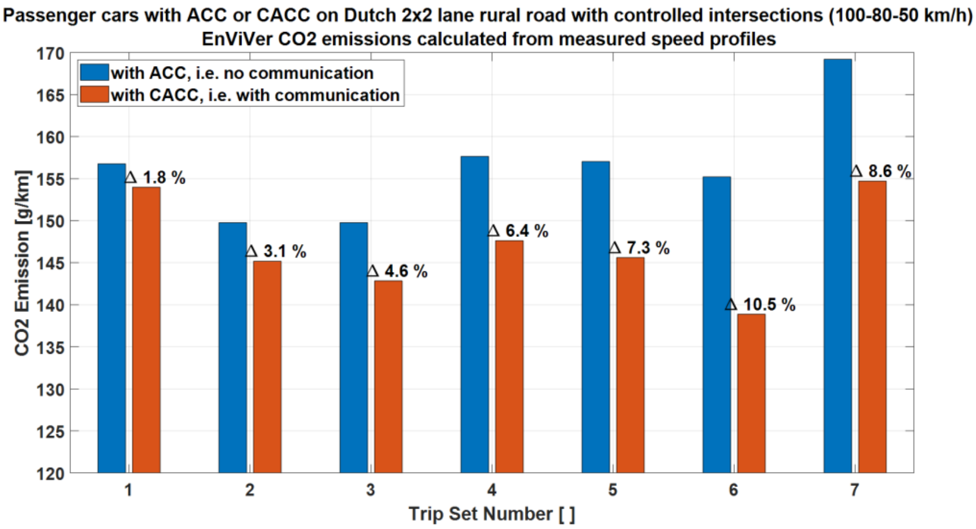

Figure 6: Emission reduction per trip, CACC compared with ACC on a 2x2 lane rural road with controlled intersections.

To give more insight into the difference in speed profiles between ACC and CACC, an example has been given in Figure 7 below. These profiles correspond to trip set number 7 in Figure 6. The first and last part of the speed profiles marked blue are removed from the calculations in order to make sure that each profile has the same length. From visual inspection of these figures it appears that the ACC speed profile has more dynamics than the CACC profiles, which was confirmed from the calculations, that showed 8.6% emission reduction.

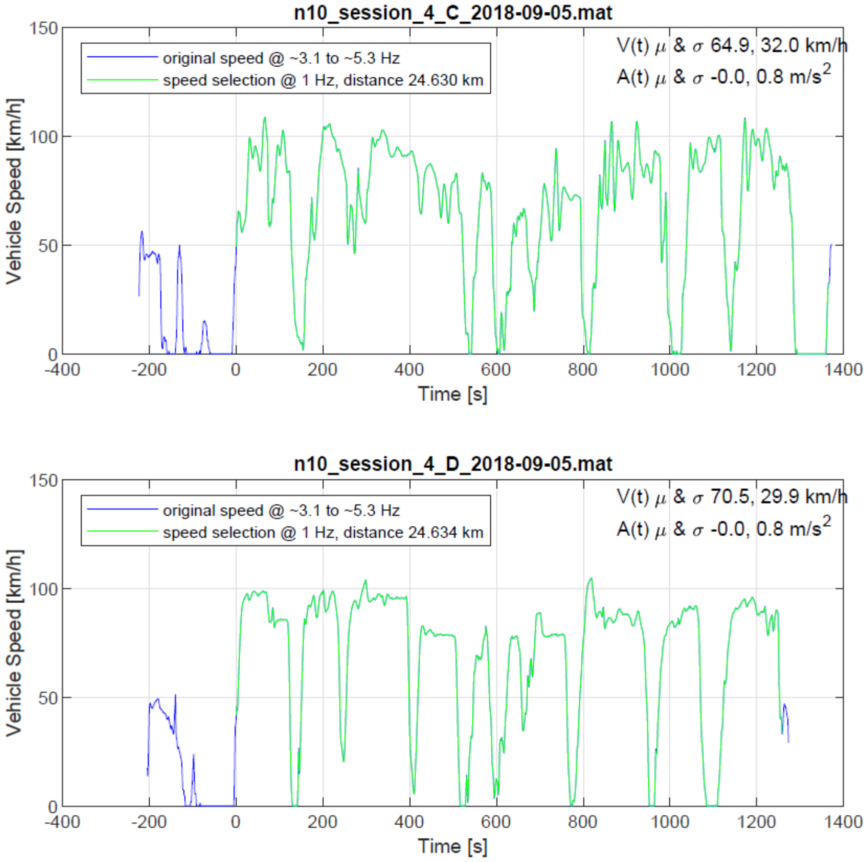

Figure 7: Comparison of speed profiles with ACC (upper figure) and CACC (lower figure).

6.5.2 Simulated motorway data with and without congestion caused by an accident

In this paragraph emissions are compared from simulated motorway data for a section of the Dutch A50 motorway, one with congestion (e.g. caused by an accident) and one without, as introduced in paragraph 6.2. The comparison is done based on the vehicle averaged emissions per km driven, calculated with EnViVer.
The potential CO_2 reduction, based on these data and calculations, is about 6% when congestion could be avoided or reduced, e.g. when making use of connectivity. See Table 11 below.

Table 11: Emission reduction potential on Dutch motorway for avoidance of congestion caused by an accident, as calculated with EnViVer for situation with and without accident and similar traffic.

	CO2	NOx	PM10	Unit
Accident	231.6	0.371	0.038	g/km
No accident	218.5	0.343	0.036	g/km
Reduction	**6**	**8**	**5**	**%**
Emissions in g/km averaged over all simulated vehicles, i.e. cars and medium and heavy trucks				

To illustrate the above results, two single vehicle speed profiles, as selected from each VISSIM simulation for the two situations, are shown and discussed hereafter. The first figure (Figure 8) shows the speed (blue) and acceleration (red) profiles of a single vehicle in the situation when there is severe congestion due to an accident. As can be seen from the speed profile, the vehicle even has to stop for about half a minute and has to brake and re-accelerate quite substantially for several times.
The second figure (Figure 9) is for a vehicle on roughly the same part of the motorway in the situation without accident and hence no congestion. In this case the speed profile is a lot smoother and the braking and re-accelerating is quite modest. This illustrates the difference in dynamics for the two cases.
Comparing the CO_2 emissions in both situations it is obvious that with congestion the CO_2 emission with congestion (574 g), resulting in a speed profile which is not smooth at all, is way higher than when there is no congestion (383 g).

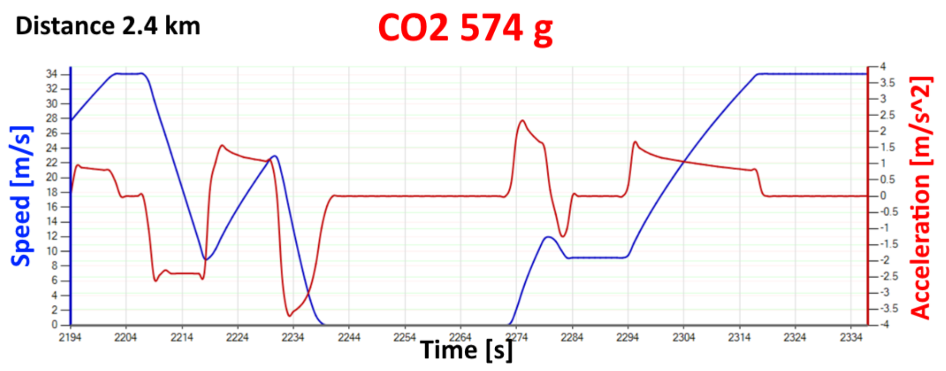

Figure 8: Single vehicle speed profile, with accident

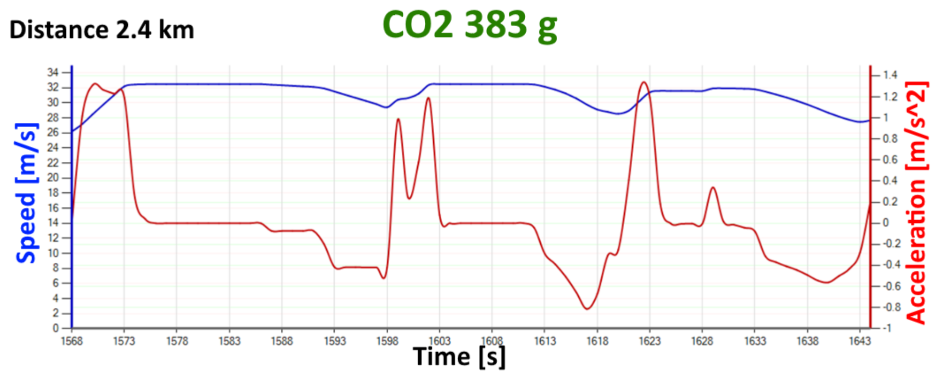

Figure 9: Single vehicle speed profile, no accident

6.5.3 Emission reductions from measured data from trucks with and without stopping at an intersection

The emission reduction potential for avoiding stops at intersections follows from measured fuel consumption data from the Catalyst program (see paragraph 6.2). This dataset contains measured instantaneous fuel consumption data from trucks, driving over intersections with a length of 2 kilometers (1 kilometer before and after).
Figure 10 shows the average emission profile of many (902) truck trips. A (median) saving of 0.12 l of fuel for the non-stopping scenario has been measured compared to the stopping scenario. This corresponds to approximately 22% (CO_2) reduction over 2 kilometers. A fuel saving corresponds 1-to-1 with CO_2 savings. N.B. In the figure it can be seen that stopping will first lead to an emission reduction when decelerating, after the intersection it increases. Other way around for ‘no stop’. Hence the fuel consumption that is used for acceleration after the intersection, is partly compensated by fuel savings from decelerating before the intersection.

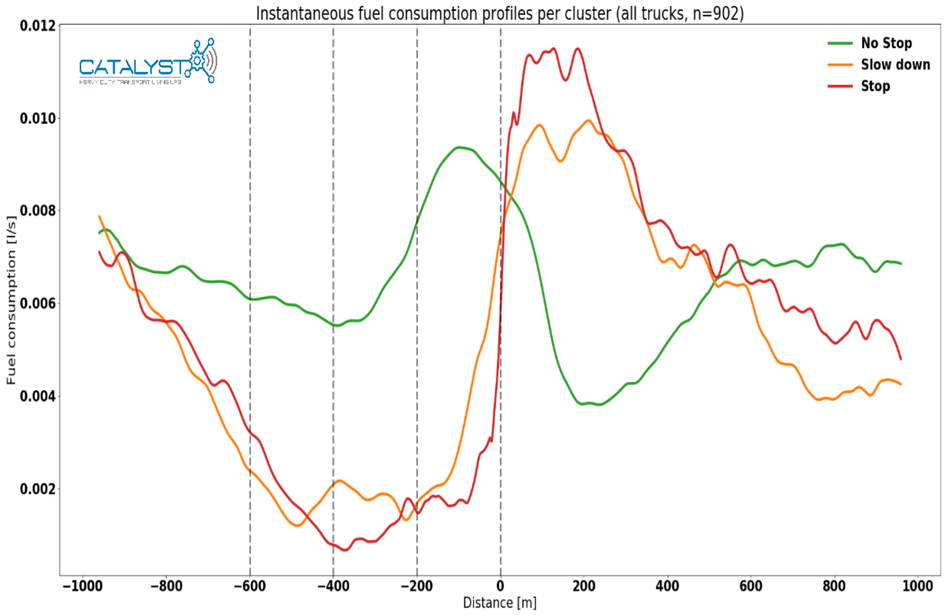

Figure 10: Average fuel consumption profiles for crossing the intersection with or without stop (No Stop/Slow Down/Stop).

6.5.4 Emission reductions when avoiding stops from simulated speed profiles

In order to perform a broader impact assessment on the avoidance of stops at intersections, additional calculations have been done with simulated speed profiles at constant speed (except during stop) without and with stop (moderate braking/accelerating at 1.5 m/s^2). Emissions are calculated with EnViVer for an average Dutch passenger car. An example of the synthetic speed profiles for a constant approaching speed of 80 km/h is shown in Figure 11.

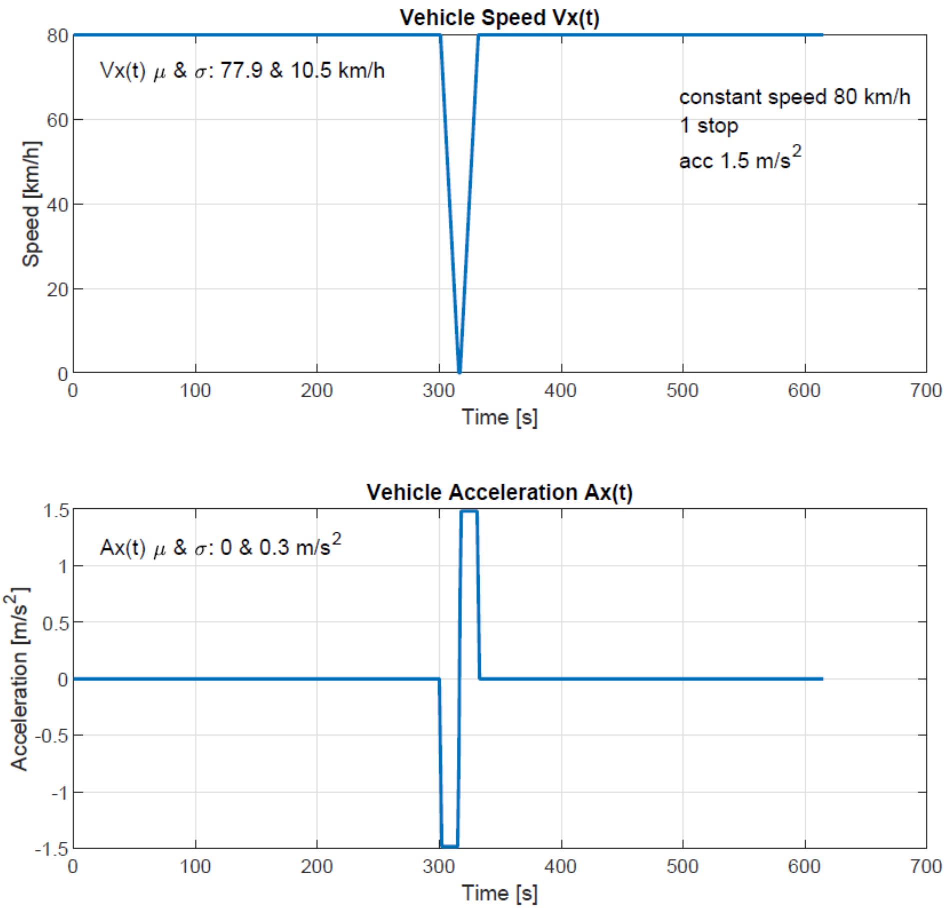

Figure 11: Synthetic speed profile for a constant approaching speed of 80 km/h used for the impact estimation for avoiding stops at intersections.

By comparing emissions with and without stops at different approaching speeds, the emission reduction potential of avoiding stops, e.g. when using communication, is estimated and shown in Table 12. The reduction potential for 1 stop per kilometer is in the range 13%-21%, with the highest relative reduction for a speed limit of 50 km/h. (The absolute effect will be higher at higher speeds.)

Table 12: Emission reduction potential for avoiding stops at intersections, 1 stop per kilometer

Constant Speed	Avoided stops	Reduction potential % per km		
km/h	per km	**CO2**	**NOx**	**PM10**
30	1	13	14	13
50	1	21	32	20

80	1	18	17	14
100	1	14	13	5

Since in practice the number of stops per kilometer varies and depends also on the speed limit, the reduction potential is also calculated for a different number of stops per kilometer, as shown in Table 13. Roads with a lower speed limit (in urban areas) usually have a higher intersection density. Because of this higher intersection density, the potential now even reaches values up to 45% CO_2 reduction.

N.B. The emission reduction measured for trucks stopping or not stopping at an intersection (mostly at 80 km/h) is higher than the result in this table (22% compared to 18 % at 80 km/h) for passenger cars. As trucks are quite a bit heavier than passenger cars the savings in fuel, and hence CO_2 reduction, can be expected to be higher.

Table 13: Emission reduction potential for avoiding stops at intersections, varying number of stops per kilometer

Constant Speed	**Avoided stops**	**Reduction potential % per km**		
km/h	per km	**CO2**	**NOx**	**PM10**
30	5	43	45	43
50	3	45	59	43
80	1	18	19	14
100	0.5	7	8	3

6.5.5 Emission reductions of smooth(en)ed speed dynamics from simulated or measured speed profiles

Finally, the potential emission reduction for reducing dynamics while driving close to a constant speed (on a motorway or urban/provincial road between intersections) is estimated, to estimate the potential of systems such as eco driving, CACC, platooning and speed harmonization. For this, simulated speed profiles for vehicles at constant and varying speed were constructed. Emissions were again calculated with EnViVer for the average Dutch passenger car.

An example of a synthetic speed profile with speed variations for an 80 km/h road is shown in Figure 12. Variations were taken from real world measurements. Emissions from these speed profiles were compared to emissions from speed profiles where all dynamics are removed (a completely constant speed).

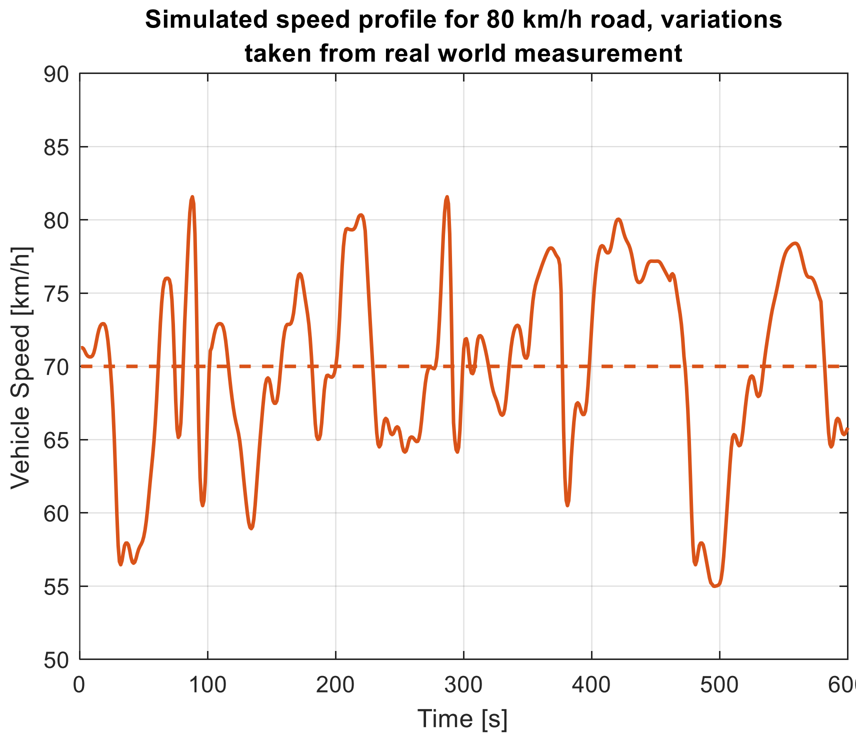

Figure 12: Simulated speed profile for an 80 km/h road, variations taken from real world measurement.

By comparing emissions by driving at varying speeds compared to driving at constant speeds, the emission reduction potential of smoothing speed dynamics is estimated. The results are shown in Table 14. This table shows that the potential CO_2 reduction ranges from 3% - 7%, with the highest relative reduction for speed limits between 50-80 km/h.

Table 14: Reduction potential for driving at varying speed compared to driving at constant speed.

Speed Limit	**Average Speed**	**Reduction potential % per km**		
km/h	km/h	**CO2**	**NOx**	**PM10**
30	**20**	4	5	4
50	**40**	6	2	6

80	**70**	7	38	8
100	**90**	3	13	3
Driving at varying speed compared to driving at constant speed. Speed variations as for traffic intensity ‘medium interaction’, resulting in average speeds below the speed limit.				

6.6 Conclusion of impact analysis

The results of the impact analysis show that substantial CO_2 reductions can be achieved by different use cases that have been selected, using communication:

1. CACC (§ 6.5.1): emission calculations using measured data from a real-world pilot on a rural road with controlled intersections, showed that using communication, in this case CACC compared to ACC, gives a benefit of on average 6% CO_2 reduction. This is purely due to the reduction of vehicle dynamics, additional savings due to aerodynamic drag reduction are not considered.

2. Eco-driving on motorways (avoiding congestion, § 6.5.2): Simulation results show that when congestion (e.g. from accidents) can be avoided, about 6% CO_2 reduction can be achieved. This case represents the potential impact that can be achieved by using communication to avoid congestion, such as with Traffic Jam Warning and Route Information systems, en-route/ on-trip (eco-driving) advice, shockwave damping systems, or safety systems that can prevent accidents. The share of congestion in km’s driven is relatively small, so it also pays to look at non-congested traffic. Therefore, we looked at the impact of eco-driving systems that smoothen the driving pattern (§ 6.5.5), based on (synthetic) speed profiles for different speed limits. the potential CO2 reduction ranges from 3% - 7%, with the highest reduction for roads with speed limits between 50-80 km/h.

3. Intelligent intersections can reduce emissions by avoiding that vehicles have to stop. In the ideal case, the traffic control can be optimized to such an extent that no vehicles need to come to a complete stop; they can smoothly pass the intersection without colliding to other vehicles when an optimal speed trajectory is used by all vehicles. The potential impact on CO2 reduction from avoiding stops at intersections depends on the approaching speed, on the vehicle type and on the number of intersections. In a large real-world pilot with trucks (§ 6.5.3), a reduction of 22% was measured on provincial intersections with a length of 2 kilometers. The simulated potential for avoiding stops (1 stop per kilometer) for the average Dutch passenger car (§ 6.5.4) ranges from 13% - 21%.

4. “Everything connected to everything”. The case “everything connected to everything” is a combination of all use cases using communication (while driving). We can assume that the impacts from the other use cases in this chapter can be applied to this use case for the complete trip, and even more benefits can be achieved with cooperative systems such as cooperative merging.

7 Possible implementations with current and future technologies

In chapter 5, the most promising use cases have been highlighted with respect to reducing emissions produced by vehicles on the roads. All these cases make use of connectivity as added value to enable the exchange of timely traffic information. Each use case has been mapped to the level at which the environmental impacts (system, traffic, or vehicle level) are targeted. In this chapter, we discuss possible architectural implementation options for these use cases with focus on communication technologies.

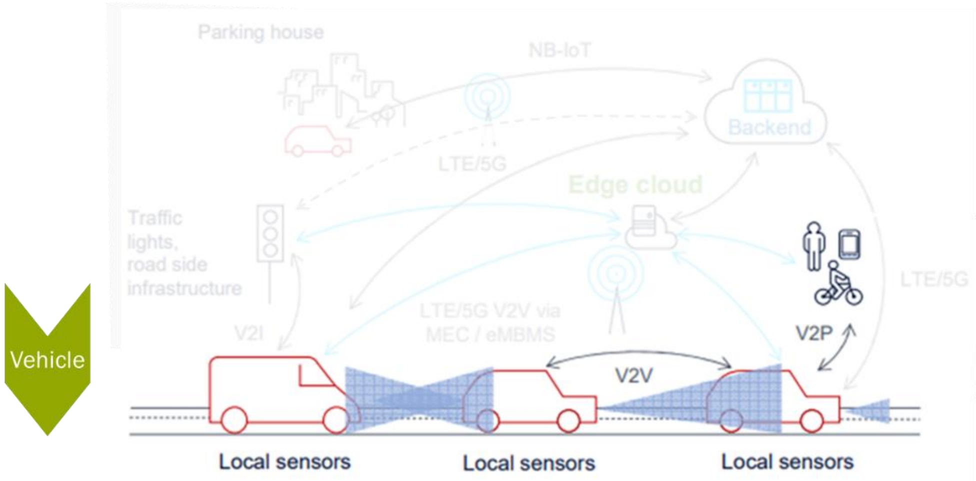

Figure 13: Implementation options with V2V communication.

When considering vehicle-to-vehicle (V2V) communication (Figure 13) via direct ad-hoc short-range V2X communication between vehicles (V2V) and pedestrians (V2P), the data exchanged mainly concerns the local vicinity around the vehicles. Therefore, V2V communication is clearly suitable for meeting the requirements of use cases having environmental impact at the **vehicle** level. Examples of such use cases are: Vehicles Platoon in Steady State, Cooperative lane merging, and B2X (e.g., bike2car).

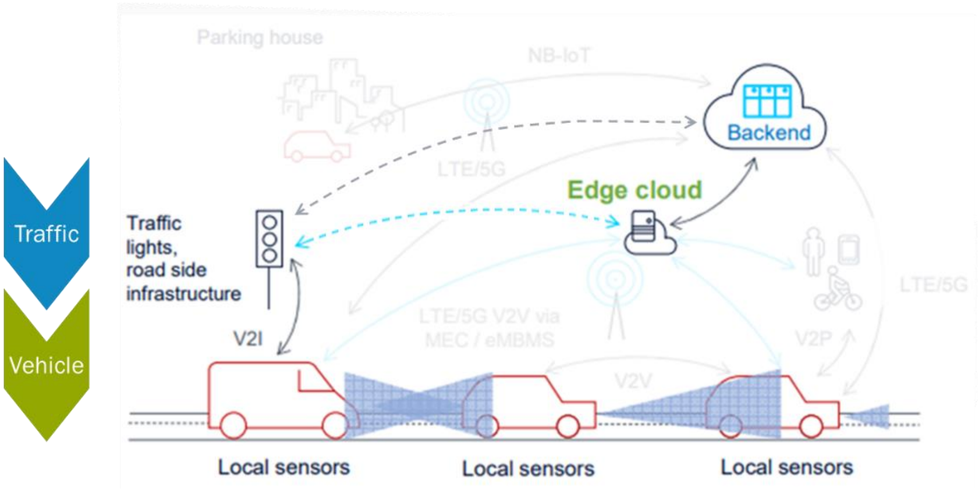

Figure 14: Implementation options with V2I (I2V) communication.

Vehicle-to-infrastructure (V2I and I2V) via direct ad-hoc short-range V2X communication (Figure 14) enables vehicles to directly exchange data with roadside units deployed alongside the road. Since roadside units can potentially be connected to a network backbone, the data scope can include traffic data originated at different architectural levels: traffic light controllers (local scope), edge cloud (mid-range scope), or even from backend servers (high-range traffic scope). This implementation option meets, therefore, the requirements of use cases having environmental impact both at the **vehicle** and **traffic** level. Examples of such use cases are: Alert systems, Speed harmonization, Continuous Traffic Flow via Green Lights Coordination.

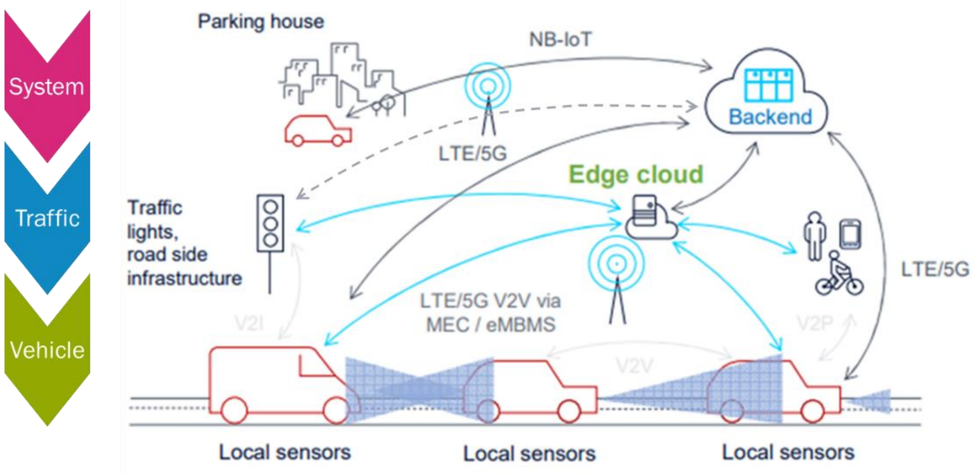

Figure 15: Implementation options with V2N (N2V), V2N2I (I2N2V), and V2N2V communication.

Vehicle-to-Network (V2N and N2V) via cellular network communication (Figure 15) relies on regular cellular base stations and core network infrastructure deployed at large scale providing long-range communication to road users. The network infrastructure may include roadside equipment (e.g., traffic light controllers) and edge cloud (mid-range scope), backend servers (high-range traffic scope), and direct access to the Internet, thereby giving road users access to virtually any available online service. Already today, services can make use of V2N communication via regular cellular networks to process and aggregate road users' data at central backend servers to, for example, enhance the functioning of traffic light controllers. This is an example of V2N2I (I2N2V) where the interconnection between roadside equipment and cellular network infrastructure can be leveraged to meet requirements of traffic and system level use cases. In addition, vehicles can potentially send data with lower latency to one another via the edge cloud deployed near the road premises (V2N2V). V2N communication can therefore meet the requirement of use cases mapped to all three clusters: **vehicle**, **traffic**, and **system** level. Examples of such use cases are: Eco-trip planning, Fuel efficiency advisor, and Continuous Traffic Flow via Green Lights Coordination.

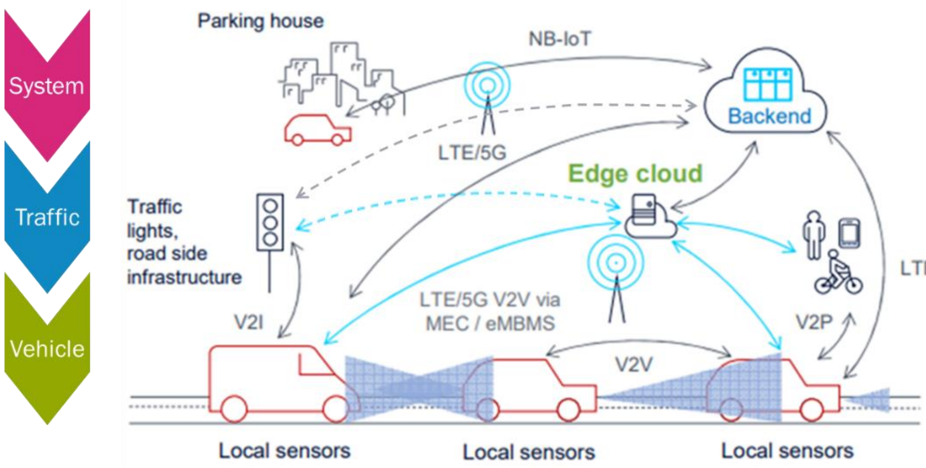

Figure 16: Implementation option with hybrid infrastructure including a combination of different communication types, e.g., V2V, V2I (I2V), V2N (N2V), V2N2I (I2N2V), V2N2V.

When combining both direct ad-hoc short-range (V2V, V2I, and V2P) and long-range communication via cellular infrastructure (V2N), various implementation options become possible (Figure 16). Such *hybrid* infrastructure gives network operators and road infrastructure providers high flexibility in terms of deployment in order to meet the requirements of different uses cases without requiring all (most) road users to support all communication technologies. Just like with V2N, hybrid architecture options can therefore also meet the requirement of use cases mapped to all three clusters: **vehicle**, **traffic**, and **system** level. Examples of use cases that can profit from such a hybrid infrastructure are: Speed Harmonization, Continuous Traffic Flow via Green Lights Coordination, "Everything connected to everything".

Different V2X communication technologies have been developed and are available already today for the implementation of V2V, V2I, V2N and their combinations (e.g., V2N2I, V2N2V). Future releases of these technologies are continuously being developed with higher degree of maturity and with the support of more advanced features.

For direct ad-hoc short-range V2X communication (V2V, V2I, and V2P), the ITS 5.9 GHz spectrum band has been assigned in Europe and in the U.S. The goal is to enable direct low-latency ad-hoc communication over short distances without relying on infrastructure. There are basically two contending technologies in this direction:

- ITS-G5 in Europe (DSRC in the U.S.) uses as basis the IEEE 802.11p standard which is an evolution of earlier versions of Wi-Fi standards. IEEE 802.11bd is the evolution version currently being specified;
- Direct C-V2X uses the 3GPP PC5 interface defined for short-range communication and it is based on enhancements for V2X defined in the 3GPP side link Device-to-Device (D2D) specification (LTE V2X in release 14). As of release 16, 5G V2X is introduced where chipset vendors are expected to integrate both LTE-V2X and 5G-V2X radio technologies at the PC5 interface, thereby supporting backward compatibility at service level.

For V2X long-range communication, the regular 3GPP Uu interface defined for LTE and 5G between UEs (i.e. vehicles) and cellular base stations is used to support vehicle-to-network (V2N) applications and services:

- 3GPP has introduced specifications for LTE (4G) in release 8 and evolved the supported features and performance with higher bandwidth and lower latency along the years up to release 14. LTE represents a significant redesign of the network architecture towards an IP-based system;
- As of 3GPP release 15, 5G has been introduced with a new core architecture, better performance and more advanced features. The concept of network ‘slicing’ has been introduced to accommodate differentiation of services, deployment options, and traffic prioritization to specific service types. In the context of V2X communication, a dedicated V2X slice could for instance be defined to meet more strict requirements of delay sensitive services while preventing interference of concurrent services and regular Internet traffic;
- As of release 16, 3GPP specification represents a major change in terms of features dedicated to V2X applications and services. It introduces additional capability to 5G NR (New Radio) in terms of short-range direct communication by further increasing bandwidth and reducing latency. Release 16 aims to meet the requirements of highly and fully automated cooperative driving use cases such as real-time situational awareness and High-Definition maps, cooperative maneuver of autonomous (e.g., platooning), sensor data sharing (collective perception), tele-operated driving, and remote software Update.

Although the combination of short and long-range communication can already be achieved with two dedicated chipsets installed in communication equipment (e.g., vehicle on-board units (OBUs)), future chipsets implementing 3GPP release 16 are expected to integrate both direct C-V2X (5G-V2X in this version) and 5G-Uu. This would bring clear advantages in terms of penetration rate of connected V2X devices in the long-term and therefore represent one step closer to enabling future use cases such as “Everything connected to everything” where real-time low latency communication is required by all road users in order to guarantee seamless coordination and smooth traffic patterns.

Overall, existing communication technologies (4G, 5G) can already meet the requirements of several of the use cases that contribute with the reduction of emissions on the roads. The more advanced features such as 5G slicing (3GPP release 15), 5G V2X (3GPP release 16) and beyond (e.g., future 6G) will only further add value and enable future use cases that require more bandwidth, Quality-of-Service (QoS) guarantees, massive equipment deployment and lower latency. For that to take place, not only the technology should be ready but also the stakeholders involved (policy makers, OEMs, Telco and road operators, etc.) should jointly cooperate to create clear business models for these future use cases.

8 Conclusions and discussion of the study

The overall goal of this study is to provide insights into the emission reduction potential of C-V2X large-scale deployment including and beyond day 1 services (see C-ITS Platform Final report 2016). The study comprises several steps to identify promising use cases: a review of the available literature on the environmental impact of C-V2X use cases, interviews with stakeholders about potential future use cases with expected substantial benefits, and identification of promising use cases based on how travel behavior and driving dynamics can be influenced. The resulting list of promising use cases (see chapter 5) shows that there is potential for C-V2X services to reduce emissions at several levels: targeting driving dynamics of individual vehicles, traffic flow management or travel behavior such as transport mode choice, destination choice, departure time choice or the choice to make a trip or not. Benefits will not emerge from communication technology directly, but from communication-facilitated transformations at all levels (proper application deployment strategies, triggering of travel behavior changes, smoothening of traffic flow).

Conclusions
The reduction potential of C-V2X services has been shown in various real-world pilots, driving simulator studies and traffic simulation studies. In addition to results found in literature, we carried out indicative calculations with a microscopic emission calculation tool (EnViVer), using speed pattern data from real-world pilots and microscopic traffic simulations carried out by TNO. We used hypothetical speed patterns to illustrate the potential of future use cases where vehicles drive with minimal dynamics (enabled e.g. by coordinated movements between vehicles). We also analyzed how the identified C-V2X services could be deployed considering the available communication technologies as well as technologies expected in the future.

What stands out from the **literature research** is the fact that most of the case studies providing quantitative results on environmental impacts are focused on applications for on-trip purposes. These are most commonly achieved due to smoother traffic and reduction of vehicle dynamics. Therefore, the center of attention has been the vehicle level, but in most of the cases the impacts are assessed on a traffic level, which offers a better perspective on the real potential. Very often the studies suggest the combination of different services and applications for the achievement of better results, implying the need for communication technologies able to facilitate concurrent services with different requirements on the network, such as minimum bandwidth and maximum allowed latency. Most of the studies have used simulation as a tool, and much less often field studies with test vehicles in real-world, although some of the approaches included first a field study and then used simulation for scaling up the results. The results differ widely due to diverse conditions in testing, in terms of penetration rates, road types and network environment, time of day etc. The denser traffic is, the more difficult it is to keep driving dynamics at a minimum. Cooperative services such as CACC and shockwave damping can be very effective also in busy traffic, but results depend on the penetration rate (and headways settings). All this explains why smaller and larger effects were found in different studies for the same type of services.

Figure 17 shows the range of effects, expressed in CO_2 emission reductions, as described in literature.

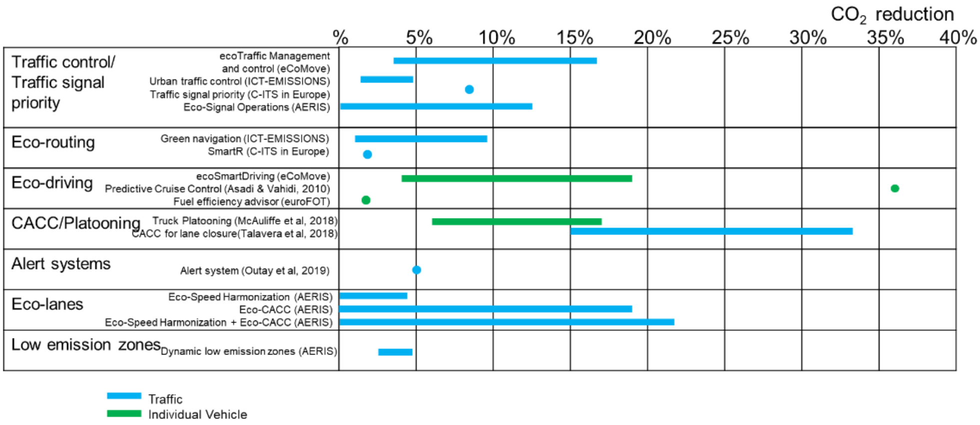

Figure 17: Impacts of different applications classified per level on which the impact is described.

The overall conclusions that came from the **interviews** with the different experts is that a long-term vision of the transport system is hard to conceive and envisage right now. However, as indicated, in order to battle several existing traffic inefficiencies the role of better, more direct communication technologies that allow the cooperation and coordination of all road users and infrastructure, can be proven to be valuable, in order to ensure as large a potential in environmental benefits as possible. The current view on the environmental benefits is not very clear, due to differences in the services offered and applied, as well as the penetration rates. A shared view by all the interviewees was the potentially large, but still uncertain, benefits due to modal shift, and a high potential for a scenario where all road users and traffic management systems are connected to each other to optimize traffic flow. This so-called “everything connected to everything” use case is a concept, to be established by the implementation of numerous use cases. The effect which can be gained by it consists of the combined effect of all these individual use cases. Our indicative emission calculations provide a first insight of what these overall effects could be.

The results of our **indicative emissions calculations** with real-world, simulated and synthetic data show that avoiding stops in any way is very beneficial (local CO_2 emission reductions in the range of 13-45%, depending on the speed limit and number of stops per km). Reducing the driving dynamics (amount of deceleration/acceleration) shows reductions in the range of 3-7% in situations where reducing driving dynamics is possible (note that this becomes more difficult the higher the traffic densities are). Services helping to avoid congestion could reduce emissions by 6% (extra emissions caused by congestion). Going from ACC to CACC also showed emission reduction effects of about 6%, due to less vehicle dynamics. N.B. The effect of aerodynamic drag reduction, when driving closely together, possible with CACC, is not included in this result.

Considering the expected evolution of connectivity and increasing levels of experience with (and potential integration of) C-V2X applications, also for emission reduction purposes, it can be assumed that the effectiveness of services will increase over time. Looking at the list of promising use cases, it can be seen that for each part of a trip, services are available that can help reduce emissions:

- Eco-driving services for situations where the driver (or the vehicle, with higher levels of automation) can anticipate the situation ahead and is mostly free to choose an optimal speed and acceleration pattern.

- Services assisting the driver/vehicle to efficiently negotiate intersections (whether signalized or not), such that the number of stops is minimized.
- Services assisting the driver/vehicle to efficiently negotiate busy/congested traffic situations where lane changes are required (merging onto or exiting a motorway, weaving sections, etc.), such that the entire traffic flow is optimized.
- Services influencing and/or harmonizing speeds to such an extent that congestion can be avoided, decreased or resolved (e.g. shockwave damping, but also CACC).
- Services assisting the driver to choose an optimal route (route optimization based on minimizing emissions, avoiding congestion).

Given that reductions in emissions in the order of magnitude of 5%-20% were found (at the local traffic flow level, resulting from various promising use cases), and that we found a similar range with our indicative impact analysis, it can be argued that if C-V2X services become available on a much larger scale and are geared towards emission reduction, they can contribute substantially to the reduction of CO_2 (and other) emissions. In an “everything connected to everything” scenario, emission reductions are possible for each part of a trip that motorized vehicles make. In addition to that, having ubiquitous, high-bandwidth and low-latency connectivity that enables e.g. MaaS and logistics services can also help travelers and freight companies make choices that result in avoided trips, change trips to different times of the day (e.g. at nighttime, for truck platooning) or lower mileage (working from home, using a bicycle and/or train instead of a car, using an electric shared vehicle instead of an own car, sharing rides, etc.). MaaS, ride sharing, and other shared mobility services are therefore also very promising use cases for reducing emissions (see also 5GAA Position paper on environmental benefits of CCAM). The literature review yielded relatively few sources clearly (and realistically) describing such use cases. Further research is needed to elaborate their potential.

Discussion
We presented in this report **results for specific situations**. No scaling up in time and space has been done. The total effect of measures is determined by the share of the situations where a measure has an effect in the total mileage (or the total emission of CO_2). For some use cases, also the penetration rate plays a role – applications where a connection to other vehicles is needed (e.g. CACC or merging assistant) need a minimum penetration rate to be effective (this minimum can be as high as 100% for truly cooperative applications). Other applications may have benefits for each individual vehicle that is equipped and/or for each part of the infrastructure that is equipped. A more extensive comparison of the different effects found, or a conclusion regarding the combined effect, is not possible within this study given the limited timeframe.

It should also be noted that possible **rebound effects** have not been assessed. In cases where C-V2X services lead to much improved traffic flows on previously congested routes (resulting in substantially reduced travel times), this can also lead to the generation of more motorized traffic (latent/induced demand). This could result in increased emissions. Also, if automated driving reaches higher levels and, for instance, automated taxis would become a very popular means of transport (because they are a fast, convenient, and cheap mode of transport), this could result in higher mileage and more emissions (however, this also depends on the powertrain/energy carrier of the vehicles). As, for instance, mentioned in Wadud et al. (2016), the overall energy and environmental implications of automation in the future will depend upon:

- The degree to which energy-saving algorithms and design changes are implemented in practice.
- The degree to which automation leads to system-wide changes that facilitate energy savings, e.g. shared vehicles, adoption of alternative propulsion technologies and fuels.
- The degree to which reduced driver burden (and reduced cost of time spent in the vehicle) leads private travelers to spend more time and travel greater distances in their vehicles or leads to greater commercial roadway activity.
- Policy responses at the federal(/national), state(/regional), and local levels.

It should also be noted that quite some services, which were analyzed on their emission reduction potential, were initially designed for traffic safety and/or traffic efficiency or even travel comfort. This also implies that future (C-V2X) services, not primarily designed for emission reduction, will nevertheless generally have emission benefits. Traffic safety, traffic efficiency and traffic sustainability are therefore inter-connected.

Developments in vehicle propulsion and design also need to be considered when looking at the emission reduction potential of promising use cases. In the future, the traffic composition will change, with an expected higher share of “cleaner” (hybrid or fully electric) vehicles. Thus, both the absolute and the relative impacts will change. In fact, if in 2050 all vehicles are zero-emissions vehicles, using renewable energy, the only effect that will still be there is reduced demand for sustainably produced energy, via the energy use per km and via km’s not driven. Also not considered in this study are aspects such as vehicle downsizing/resizing, CO_2 emissions as a result of manufacturing (less) vehicles, and the carbon footprint from 5G deployment.

The **system level analysis** part of the study has shown that different implementations, using different (combinations of) communication technologies are possible for the deployment of the C-V2X services. The added value of connectivity for sustainable goals can be gained in several ways. Much is possible already now with the current existing long- and short-range communication technologies, such as LTE, LTE-V2X and ITS-G5. It is important to realize that under the 3GPP roadmap new features can become available in the near future, suitable for deploying multiple concurrent services with different requirements. Concurrent services have requirements such as:

- Minimum bandwidth: new frequencies and technologies can provide sufficient bandwidth for multiple, more advanced services;
- Guaranteed performance: Slicing enables better Quality of Service for individual V2X services without interference of other concurrent services, like ‘regular’ Internet services;
- Maximum allowed latency.

The 3GPP architecture as shown in chapter 7 allows for a scalable implementation, with both local (edge servers) and national (central servers) components, and short- and long-range communication. The different requirements of the services (maximum allowed latency, minimum required bandwidth, global vs local coverage, best–effort) can be met by these different solutions. An integrated 5G-V2X and 5G-Uu chip, which is promised to become available, would drastically increase the coverage for short (and long) range services, as “all” connected devices would automatically support both channels.

This added value will have to prove itself. Some features are now only planned, and whether all possible functionality will be available is not just a technical question, but also a business case question. Stakeholders to include here are among others industry, public authorities and end users.

Recommendations for further study
In the conclusions and discussion, several aspects were raised that can affect the magnitude of the emission reductions but were not researched in this study. Topics that need further study are:

- What is the potential of promising use cases when widely available in time and space and/or when combined? This requires looking at methods to scale up in time and space – which part of a trip can be made more efficient, and when (in which situations/traffic conditions) is it very difficult to improve efficiency (e.g. oversaturated networks)? What are the combined effects of bundles of services?
- Following from that: What would the “everything is connected to everything” scenario look like and what emission reductions could be achieved, when considering present vehicle fleets but also future vehicle fleets (in 2030, 2040, 2050)?
- Wat are the effects of vehicle fleets getting cleaner and more energy-efficient? How does this affect the relative and absolute effectiveness of promising use cases in various regions? Questions regarding the electrification of the vehicle fleet and the necessary infrastructure, as well as sustainable energy sources for that, are connected to this.
- Which rebound effects can be expected when the traffic and transport system – or the entire mobility system– is made more efficient and thus more attractive? Which rebound effects (e.g. more trips, longer trips) do we need to consider?
- What are the expected effects of use cases/services that are used pre-trip, such as MaaS-applications or real-time traffic information & route planning services? Which share of travelers is open to options like a mode shift to a more sustainable mode of transport, ridesharing or travelling outside peak hours? What would this mean for the modal split, both in terms of trips and in km’s driven?
- The study presented several ways of how the use cases identified could be implemented, with V2V, V2I and V2N possibilities. Topics for further research considering the implementation are to analyze which implementation is preferred in which situation, and what the influence of the way of implementation on the benefits would be.

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10 Signature

The Hague, 16 November 2020
TNO

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A Longlist

	Source
1	**A Review on Energy, Environmental, and Sustainability Implications of Connected and Automated Vehicles** Morteza Taiebat, Austin L. Brown, Hannah R. Safford, Shen Qu, and Ming Xu
2	**Eco-Driving Systems for Connected Automated Vehicles: Multi-Objective Trajectory Optimization** Ke Huang, Xianfeng Yang
3	**Project SimTD** Safe Intelligent Mobility Test Field Germany Jan 2008 - Jul 2014
4	**Project EcoDriver** Supporting the driver in conserving energy and reducing emissions - Low carbon multi-modal mobility and freight transport. October 2011 – March 2016
5	**Project eCoMove** Cooperative Mobility Systems and Services for Energy Efficiency - ICT for Safety and Energy Efficiency in Mobility April 2010 – January 2014
6	**ACEA report** Joining forces to tackle the road transport CO_2 challenge - A multi-stakeholder initiative.
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15	**5G CARMEN**

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28	**Meta-Analysis of Adaptive Cruise Control Applications: Operational and Environmental Benefits** Eilbert, A., Berg, I., & Smith, S. B. (2019).
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B Shortlist templates review

EU Project eCoMove

Source reference	**EU Project eCoMove** **Cooperative Mobility Systems and Services for Energy Efficiency** ICT for Safety and Energy Efficiency in Mobility2010-2014
Use cases mentioned	**eCoMove core technologies**: – V2V & V2I/I2V communication platform based on CVIS & SAFESPOT projects results. – Standardized cooperative messages for energy efficiency-relevant information exchange – ecoMap (digital map database enhanced with eco-relevant attributes) **eCoMove applications** – <u>ecoSmartDriving</u> applications for fuel-efficient driving behavior – <u>eco Freight & Logistics</u> applications for green freight routing and fuel consumption- optimized logistics – <u>ecoTrafficManagement & Control</u> applications for energy-efficient traffic control & management measures Intended improvements: -Saving unnecessary kilometers driven (optimizing routes) -Helping driver to save fuel (optimizing driver behavior) -Managing traffic more efficiently (optimizing network management)
Region	Aachen, Munich city and Motorway network, Germany DLR in Braunschweig, Germany Helmond, The Netherlands (simulations)
Method applied for obtaining impacts	The developed eco-applications for cars, trucks and traffic management have been validated using three different approaches: (1) **field trials** (1 Ford car, 2 Fiat cars, 1 BMW car + VOLVO and DAF trucks, with automated gear boxes), (2) **traffic simulations** (VISSIM and EnViVer) and (3) **driving simulator studies**. The results from the field trials, and the driving simulator studies, were used to derive parameter settings for the microscopic traffic simulations, which provided impact assessments for several penetration rates. 30 people undertook simulated drives with and without an eco-driving advice system using a visual HMI and a haptic pedal. The simulator was used with a simulated lead car (i.e. the “driver” was behind another car) and without a lead car (i.e. clear road ahead). Different advice speeds were given on approaching these features (traffic light, stop sign, curve).
Impacts found	**Simulation and on-road trials results:**

	EcoSmart Driving: Eco-driving HMI: (Ford Focus) 11% fuel reduction, (Fiat 500 and Fiat Qubo) 4.5% fuel reduction in a mixed urban-interurban route in Turin area. eCoAssist: (BMW 535i demo vehicle) 18.6% fuel savings in a mixed urban-interurban route near Munich. Eco-driving with haptic pedal: 15.9% calculated reduction in fuel use on simulated urban road (50 km/h) and 18.4% on simulated rural road (70 km/h). Varying from saving 1.3%, when no reduced speed was advised before traffic light, to saving 36.8%, on approach to urban/rural traffic lights without a lead car where a low recommended speed was given. **EcoTraffic Management and control**: EcoBalanced priority: For motorway on-ramps the CO_2 emissions can be reduced with 14-17% depending on the traffic volume. The effect on the motorway itself is smaller. ecoRamp metering: 5.1% CO_2 reduction, 9.4% NOx reduction, PM10 11.7% increase (scenario 100% penetration rate). In Munich, the **ecoApproach Advice** shows an improvement for the CO_2 emissions of cars of up to 10%, for trucks up to 16% and the combined applications **ecoBalanced Priority** and **ecoApproach Advice** show an improvement up to 15% for cars, while for trucks up to 14%. **ecoApproach Advice** and **ecoGreen Wave** shows an improvement for the CO_2 emissions of cars up to 11 %. This effect increases with the penetration rate. On the other hand, the CO_2 emissions for trucks increase up to 16 %. The reason for that is the lower driven speed between the signalized intersections. According to the emission model the CO_2 emissions increase by 37 % by reducing the speed from 60 km/h to 40 km/h. For trucks no added effect can be seen. For higher demands this effect is smaller as the ecoGreen Wave does not adapt the green time split. Coordination is only effective for not oversaturated traffic streams. The application of a **model predictive controller** as opposed to the more traditional traffic actuated controller is beneficial in both, in terms of travel time reduction of approximately 15.5%) and in terms of CO_2 reduction of up to 9.3% (plus 7% at 100% penetration). Together with ecoApproachAdvice the amount of CO_2 emitted can in both cases be reduced with an additional 7%, assuming a 100% equipment ratio. For the peak-hour this comes with a small cost in travel time. For the off-peak hour

	the impact of the ecoApproachAdvice application on travel time is however negligible.
Assessment reliability of results	On a general level, the eCoMove applications show good results concerning the reduction of emissions in the field of traffic signal control. However, under specific conditions the delay on main routes or even the whole network might, in parallel to the reduction of emissions, increase. eCoMove applications for traffic management and control from a network perspective show an average reduction of emissions exceeding ten percent. Also, eCoMove driving behavior support is found to reduce CO_2 emissions and traffic queues, the number of stops and the individual travel time but might result in higher delays in side routes. Concerning the eCoMove route advice and detour recommendations the simulations show that the networks do not suffer from negative impact if up to ten percent additional traffic load is generated on specific routes due to the eCoMove advice. In parallel, the eCoMove route advice is seen to reduce CO_2 emissions in the lower one-digit percentage range. The eCoMove applications will not have the desired impact at very low penetration rates. Penetration rates (road-side units and on-board units) need to reach certain levels for optimal operation. The optimal level (from a benefit-cost ratio point of view) depends on the application: some applications already show substantial impacts at relatively low levels of penetration of on-board units (e.g. 10%), although (in the case of I communication) only in areas where the infrastructure equipment rate is high. Other applications show ever increasing impacts with increasing penetration rates (but may have lower benefit-cost ratios at higher penetration rates). For some applications, it could be useful to start with, or limit the use of the system to specific fleets, such as public transport and/or emergency vehicles, or heavy goods vehicles. As a general conclusion, most of the expectations especially concerning the reduction of emissions could be met or even surpassed by the eCoMove applications, although, in rare cases, collateral effects might have a negative impact on the traffic situation. *Overall, a 20% reduction seems too ambitious, but the results of the tests carried out in the eCoMove project show that a reduction > 10% is feasible in urban networks (expectation based on expert judgment of the eCoMove project team).*
Transferability of results	The extent of the effects depends on the traffic situation, the road network, and the driver.
Scalability of results	Integration of several functionalities is needed: route choice influences the navigation and the current route (hence the ecoCooperative Horizon). On the local level, cooperative traffic lights can help reduce the number of stops. This integration has taken place in eCoMove but needs to be improved for large

	scale deployment. An aspect to consider is knowledge about the direction the vehicle is taking at an intersection so the most probable path can be calculated more accurately. It is also desirable to adapt the navigation application for touchscreens. Initially, it was aimed to **scale up** the results to a larger local or regional level, e.g., the whole North-Western Munich network or the region of Munich. During the project it became clear that this was not possible, for several reasons.
Feasibility assessment of use cases	(Innovative) business models for cooperative systems need to be defined (who pays for OBUs, RSUs, maintenance). The application is expected to cost more than private customers or fleet owners are willing to pay. Customers are not willing to pay more than a very small amount until they know the system and its potential benefits very well. Political/ cultural barriers. Some specific combinations of eCoMove applications proved incompatible during the simulations and the related test setups were dropped, partially replaced by new ones. The eCoMove system is complex with many components, applications and core technologies interacting with each other. This led to difficulties with the interpretation of data and messages in several chains of linked components, applications and core technologies (which were often implemented by different partners). Lacking map data, e.g. no accurate altitude (or slope) data. Differences in map data between ITS stations may be as problematic as having no map data at all. It is not feasible to solve this by creating “one map for all” – instead, different ITS stations should be expected to have different maps, and V2X communication is required to be map agnostic. This way of thinking is not common yet. eCoMove solutions are expected to only be feasible in combination with other solutions, and it is unknown when those will be available.

EU Project ICT-EMISSIONS

Source reference	**EU Project ICT-EMISSIONS -Low carbon multi-modal mobility and freight transport** Development of a methodology and tool to evaluate the impact of ICT measures on road transport emission 2011-2015, https://cordis.europa.eu/project/id/288568
Use cases mentioned	Impact on energy and CO_2 of **infrastructure measures** (traffic management, dynamic traffic signs, etc.), **driver assistance systems** and **ecosolutions** (speed/cruise control, start/stop systems, etc.) or a combination of measures (cooperative systems).

	○ **Variable speed limits** (VSL), Madrid: 3-lanes motorway, 6.6 km length. ○ **Green navigation** (GN): Real-time in-vehicle navigation for eco-routing, by PDA or mobile phone (Madrid) ○ **Urban traffic control** (UTC), Turin (micro level) and Rome (micro and macro level): influences traffic flows allowing to reduce fuel consumptions and CO_2 emissions by synchronizing and optimizing traffic lights along urban axes. V2I communication. ○ **Eco-driving** (Madrid and Turin) ○ **Start and stop** (Madrid, Turin and Rome) ○ Adaptive Cruise Control (**ACC**): Automatic velocity control subject to the distance to the preceding vehicle (Munich and Turin)
Region	Turin, Madrid, and Roma areas.
Method applied for obtaining impacts	The proposed methodology combines traffic and emission modelling at micro and macro scales. Simulation of several thousand ACC vehicles (different fleet compositions: 2013, 2013 Hybrid, 2014, 2014 Hybrid, 2030) for urban ring road and city streets. VSL have been modelled at micro level with PTV VISSIM, with an integrated control algorithm, while the emissions at this level have been calculated with AVL Cruise. Following micro-to-macro interface procedure, PTV VISUM simulates the traffic at macro level and COPERT the emissions. GN: VISUM (30 scenarios for emissions calculations). UTC: for Turin AIMSUN was used, which includes the possibility of simulating UTC measure with adaptive control interface UTOPIA. The GIPPS extended car following model, estimated with FIAT ecodrive data of standard user, was used in four scenarios. In Rome, micro model assignment was carried out by using PTV-VISSIM, while macro traffic model is developed in Transcad. Eco-driving: simulated first at the micro level and the result is then scaled up to the macro. Emissions have been calculated with either CRUISE (at micro level) or COPERT at the macro level). Start and stop: simulated at micro level only (VISSIM and AIMSUN), for passenger cars only. The emissions are calculated using AVL CRUISE. ACC: integrated in a microscopic traffic simulator such as Aimsun or SUMO via plugins. Two urban scenarios selected in Munich. On-road trials in Madrid for navigation and eco-routing.
Impacts found	**VSL**: both absolute and relative CO_2 emissions savings around 1.5%. **GN**: Modelled results for 2014 car fleet: under medium traffic conditions 1.1% CO_2 reduction with 10% penetration rate, rising to 4.7% with 90% penetration rate. In congested traffic, benefits are higher: 2.2% with 10% penetration, up to 8.2% reduction

	with 90% penetration. Under free flow conditions, benefits are higher still: 5.9% to 9.5% depending on penetration rate. Results vary substantially according to the traffic level, having a positive impact for low and high traffic situations but not for medium flow. These benefits increase more with lower penetration levels, while with penetration levels over 75% it seems to reach an asymptote. Disaggregating results into road types: the benefit concentrates in motorways and highways, meaning that drivers following "the greener route" are selecting shorter routes, though this may imply crossing the city center or selecting a road with lower speed than a highway. Negative aspect: the time increase. As length has an important effect in CO_2 emissions, green drivers choose routes similar to the minimum length, even having higher travel times. **UTC**: Micro level: the decrease of absolute CO_2 emissions and relative CO_2 emissions are lower with the Italy 2030 fleet composition, probably due to the higher effectiveness of emission technologies that reduce the effects of ICT measures on the environment (-2.18% compared to -1.72% and -4.84% compared to -4.37%). Macro level: global decrease of CO_2 emissions **Eco-driving**: While the trial results in Madrid gave CO_2 reduction benefits of between 4.5% and 16.2% (average benefit of 5.5% on motorways and 12.5% on urban roads), the impact assessment showed much smaller benefits, or (rarely) even disbenefits (worsening) when modelled with higher penetration rates. This is because with 75% of drivers eco-driving on a congested urban network, the network becomes saturated (due to longer vehicle headways) and the resultant congestion then increases emissions. Relative positive effects can only be found with low levels of traffic and with eco-driving penetration rates smaller than 25%. For Turin: The ecodriver increase causes a reduction of the CO_2 emission in free (15% for 100% ecodrivers) and normal (-10% for 100% ecodrivers) traffic conditions whereas in congested traffic condition the CO_2 emission increases (+3% for 100% ecodrivers). Considering the predicted future fleet composition, the CO_2 emission would decrease according to an almost constant 1% rate in free flow condition, to a 1.3%-1.5% rate range in normal traffic condition and to a 1.7%-2.4% range in congested condition. **Start and stop**: small improvement for Madrid (small percentage of stop time). Improvement increases with higher penetration rate of start and stop vehicles. Turin: improvement in CO_2 emission reaches up to 13% for congested condition at base case for the fleet 2013. Similar as in the Rome test case the improvement is smaller for the fleet 2030 reaching only 11 %. **ACC**: Maximum modelled impact: 7.5% CO_2 reduction (for urban ring road with 100% ACC penetration rate); 4.5% with

	60% penetration and 1.5% reduction with 20% penetration. On city streets, savings were much lower (between 0.25% and 2.25% depending on penetration rate).
Assessment reliability of results	Results of the project demonstrated that ITS can help reduce CO_2 emissions, but that reductions varied substantially based on local conditions like traffic, infrastructure and fleet composition. Advanced vehicle types like hybrid and plug-in hybrid vehicles could provide additional benefits. Modelling for eco-driving was found to be a very delicate procedure as small differences in road capacity can cause negative effects on already congested networks. VSL – upscaling to macro level: results in global terms are almost insignificant, as expected due to the little area where the measure was implemented compared to the whole region.
Transferability of results	Vehicle and driving related ICT Systems can bring substantial reductions – over 15%, depending on traffic conditions. The reductions are greatest when many cars have such systems and can interact with one another. In addition, traffic and routing related systems can have an impact of up to 8% CO_2 emissions reduction, based on factors like traffic light timing which can affect local driving and road capacity.
Scalability of results	Results were scaled up to city level for two years: 2014 and 2030, to different penetration rates (from 10% to 90% of vehicles equipped) and different traffic conditions (free-flow, medium and congested).
Feasibility assessment of use cases	-

V2V and V2I Communications for Traffic Safety and CO_2 emission reduction

Source reference	**V2V and V2I Communications for Traffic Safety and CO_2 emission reduction: a performance evaluation** Outay et al. 2019
Use cases mentioned	**V2V cooperative alert system** Hazardous situations for vehicles **V2I alert system** Comparison of the performance of V2V and V2I communications in terms of road safety effectiveness and network communication efficiency. Also, exploration, via simulations, whether CHAA systems, based on V2V and V2I communications can potentially contribute towards eco-driving by reducing Carbon Dioxide (CO_2) emissions. Impact of the proposed CV safety applications on CO_2 emissions (in grams) for three scenarios: standard vehicles, slow vehicles, and trucks.
Region	Network consisting of 10km highway road segment (two lanes in each direction) with 1km hazardous zone and alert zone of 2km.

Method applied for obtaining impacts	Computer simulation experiments. Cooperative traffic safety applications for iTetris in C++. SUMO to simulate vehicle braking to the maximum deceleration and vehicle slowdown.
Impacts found	The V2V and V2I alert systems contribute towards reducing CO_2 emissions by around 5% for vehicular densities up to 3000 vehicles/hour for the three types of vehicles. This can be explained by the fact that our two CV safety applications favor speed harmonization when vehicles enter a hazardous zone, which contributes towards reducing unnecessary accelerations/decelerations and sudden stops, thus reducing fuel emissions. We also note that the V2V alert system yields better performance in terms of CO_2 emissions compared to the V2I alert system, across all types of vehicles. For the baseline scenario where there is no danger, the amount of CO_2 emitted is the lowest since vehicles are moving without any danger situation and without slowing down or braking.
Assessment reliability of results	The performance analysis is based only on (extensive) computer simulation experiments.
Transferability of results	This work departs from aforementioned contributions in two main aspects. First, no focus on eco-driving strategies for signalized arterials. Second, no intention to introduce new speed planning algorithms or additional network overhead to favor eco-friendly driving. Instead, exploration if our proposed V2V / V2I cooperative mechanisms, originally developed for road safety, could be leveraged to reduce CO_2 emissions.
Scalability of results	Currently exploring the usage of a hybrid V2X alert system that combines both V2V and V2I communications. Plan to test the proposed approach in the field in the context of a real-world experimental study.
Feasibility assessment of use cases	-

EuroFOT

Source reference	**European Field Operational Test on active safety functions in vehicles (euroFOT)** European Large-Scale Field Operational Tests on In-Vehicle Systems 2008-2012
Use cases mentioned	Eight distinct functions that assist the driver in detecting hazards, preventing accidents and make driving more efficient. The analysis of the data gathered in real-world traffic conditions with ordinary drivers is expected to highlight several crucial aspects of intelligent vehicle systems: - What are the performance and capability of the systems? - How does the driver interact with and react to the systems?

	- What are the impacts on safety, efficiency, and on the environment? Intelligent Vehicles equipped with Advanced Driver Assistance Systems (ADAS) and used by ordinary drivers in real traffic: • longitudinal control functions: Forward collision warning (FCW), adaptive cruise control (ACC), speed regulation system (SRS) • lateral control functions: Blind spot information (BLIS), lane departure warning (LDW), impairment warning (IW) • advanced applications: Curve speed warning (CSW), fuel efficiency advisor (FEA), safe human machine interface (SafeHMI)
Region	France, Germany, Italy and Sweden.
Method applied for obtaining impacts	**FOT**. Over the course of one year, more than 1,000 cars and trucks equipped with a range of different intelligent technologies are being tested on European roads. Data acquisition techniques ranged from questionnaires to continuous recording of vehicle signals, and, in some cases, additional instrumentation with video and extra sensors. Additional to the effect on fuel consumptions, the function for which the highest environmental benefits were expected, being ACC and SRS, an **emission model** was used to determine the CO_2 and the regulated emissions CO, NOx, PM10 and HC. The model used speed-time profiles observed in the FOT to determine the emissions. In addition, **simulations** were used to calculate also effects of the ACC use on regulated emissions (CO, NOx, PM10, HC) as well as CO_2. As input to these simulations speed profiles gathered in the FOT were used. The data set included almost 100 hours of driving time from nine different drivers.
Impacts found	**FEA**: The treatment phase showed a reduction in fuel consumption of 1.9% based on 3.6 million kilometers from 50 trucks. Significant reduction in fuel consumption while driving with **ACC** and **FCW** for both vehicle types (passenger cars and trucks). For passenger cars: a decrease of 2.77%, for trucks: 1.78%. The overall fuel saving potential for passenger cars is 1.37% and slightly below 1% for trucks. This accounts for 790 million liters of fuel every year and almost 2 million tons of CO_2 based on the average fuel consumption that was evaluated with the objective data. However, the results for trucks seem more reliable since the driving patterns that are compared in baseline and treatment are very similar because of the general traffic and driving situation (car following situations with little speed variation). **SRS**: significant influence on the fuel consumption on all road types. The reduction varies between 1.55% on motorways, 3.75% on rural roads, and 5.19% on urban roads. These

	results might be influenced by the choice of the driver when to use the system. The higher influence of the SL at lower vehicle speeds is due to thermal engine fuel consumption which is lower for high speeds until 90 km/h. For higher speeds the fuel consumption increases again. The reduction can be attributed to a more constant speed while using **SL**. For all road types a significant influence of the use of **CC** on the fuel consumption was found during the analysis. The reductions vary between 1% for motorways, 13.2% on rural roads, and 36.3% for urban roads. From simulation: Considering usage rates for the different road types the effects on CO_2, HC and PM show a very small increase of less than 1%. Only CO and NOx emissions show increases higher than 2% on motorways. The following quantified environmental impacts were provided to the **CBA** (at the EU level): • Direct effects: change in fuel consumption and CO_2 emissions caused directly by a change in tactical driver behavior (e.g. speed, acceleration) • Indirect effects: change in fuel consumption and CO_2 emissions caused by a change in kilometers driven (for example less congestion due to less accidents)
Assessment reliability of results	The fuel consumption was directly measured from the CAN data in the FOT and tested for significant effect using statistical tests. The effect is the difference between the average fuel consumption per kilometer in the baseline period and the average fuel consumption per kilometer in the treatment period when the function is active. It is then scaled for the usage based on mileage. This means that the usage as observed in the FOT is considered. The fuel consumption was determined per road type or speed, limit considering the variance between drivers. Generally, ANOVA tests were used. SRS/CC: the high influence on urban roads might be caused by the selection of driving situations when the system is used. This inherent bias in the FOT data on CC leads to precaution in the interpretation of the results as they do overestimate the benefits. The low usage rate of 2.69% is an additional indicator that the system is only used under certain driving situations whose driving pattern might be different from the rest of urban driving.
Transferability of results	Results consider only driving on motorways and are based on the gathered FOT data. The SL environmental effects are projected for driving on motorways. It is assumed that the usage rate derived from the FOT data can be transferred to the whole EU-27. Combining the usage rate with the reduction in fuel consumption a fuel saving of 0.26% could be achieved in the European passenger vehicle fleet.
Scalability of results	FEA: Due to the very limited information on driving conditions that result in the evaluated fuel reduction and the related

	uncertainty ($p > 0.05$) scaling up the effect to EU-27 level is not applicable. Besides the micro-macro-level (FOT vs. EU-27 impacts) consideration there were also other performance restrictions which limit the applicability of cost-benefit analysis to the euroFOT (impact) results. Insufficient knowledge on EU-wide driver behavior and network characteristics: For navigation systems (Safe HMI) and simple control functions (SRS) which impacts depend on the selection of driving periods and routes for which the system is used, determining the baseline – in terms of comparable mileage – is more complex. Due to the limited availability of results, cost-benefit assessment based only on direct fuel or time savings was not applicable for SRS and SafeHMI, since up-scaling these results would require excessive knowledge on EU-wide driver behavior and network characteristics.
Feasibility assessment of use cases	Piloting should always be done with the vehicle type to be used in the FOT and enough time for adapting the data logging equipment must be calculated. Never start a large scale FOT before all components of the system are validated in production condition. Not feasible to strictly follow the FESTA methodology guidelines for data analysis during the pilot tests (unrealistic to expect ready to work software tools at the time the data collection begins). Piloting tests cannot be made with external subjects. Piloting tests should continue during the ramping up of the FOT. The feasibility of cost-benefit analysis was narrowed down due to non-applicable and / or significant impacts as well as performance restrictions in up-scaling to EU-27 level.

Study on the deployment of C-ITS in Europe

Source reference	Asselin-Miller, N., Biedka, M., Gibson, G., Kirsch, F., Hill, N., White, B., & Uddin, K. (2016). **Study on the deployment of C-ITS in Europe: Final Report**. Report for DG MOVE MOVE/C, 3, 2014-794.
Use cases mentioned	The report analyses different scenarios and presents the conclusions for scenario E. There are 5 scenarios (A-E) in which E assumes most action by the EU. In scenario E all considered V2X services (25 total) are implemented. It must be stated that the expected results are compared to a base case in which the EU takes no action, but it is assumed that services are implemented by other parties (as they expect now). Additionally, in the appendix the expected effects are listed separately for all these 25 services. The 4 most promising (largest CO_2 benefits) are listed below. 1. In-vehicle speed limits (VSPD)

	2. Green Light Optimal Speed Advisory (GLOSA) / Time to Green (TTG) 3. Traffic signal priority request by designated vehicles (TSP) 4. Traffic information and smart routing (SmartR)
Region	Use cases are from different locations. Results are aggregated to EU27 level.
Method applied for obtaining impacts	The study uses data from field tests/pilots, FOT / naturalistic driving tests, and literature as input for a modelling environment (ASTRA/TRUST). For the 4 use cases the data comes from: 1. In-vehicle speed limits (VSPD) DRIVE C2X (TNO, 2014) 2. Green Light Optimal Speed Advisory (GLOSA) / Time to Green (TTG) DRIVE C2X (TNO, 2014) 3. Traffic signal priority request by designated vehicles (TSP) UITP Working Group (TfL, TRL, University of Southampton, 2009) 4. Traffic information and smart routing (SmartR) (TNO, 2009)
Impacts found	Overall results (scenario E): Fuel consumption is reduced by c. 2.4 million toe/year by 2030, or c. 1.2% of baseline fuel consumption. CO_2 emissions are reduced by c. 7,500t/year by 2030, or c. 1.2% of baseline emissions. NOx emissions are reduced by c. 4,500t/year by 2030, or c. 0.7% of baseline emissions in that year. CO emissions are reduced by c. 4,300t/year by 2030, or c. 0.4% of baseline emissions. VOC emissions are reduced by c. 700t/year by 2030, or c. 0.4% of baseline emissions. PM emissions are reduced by c. 150t/year by 2030, or c. 0.5% of baseline emissions. Per use case: **In-vehicle speed limits (VSPD)** If displayed continuously: 2.3% fuel saving on motorways and a 3.5% fuel saving on non-motorway non-urban roads. NOx: 0.5% reduction (motorways), 0.4% reduction (non-motorway non-urban roads), zero change (urban roads) PM: 0.4% decrease (motorways), 4.2% increase (non-motorway non-urban roads), zero change (urban roads) CO: 0.2% reduction (motorways), 0.2% increase (non-motorway non-urban roads), zero change (urban roads) VOCs: 0.1% increase (motorways), 0.5% increase (non-motorway non-urban roads), zero change (urban roads)

	Green Light Optimal Speed Advisory (GLOSA) / Time to Green (TTG) 0.1% reduction in fuel consumption on rural roads and a 0.7% reduction in fuel consumption on urban roads. CO: 0.3% reduction (non-motorway non-urban roads), 0.8% (urban roads) NOx: 0.1% reduction (non-motorway non-urban roads), 0.2% (urban roads) VOCs: 0.5% reduction (non-motorway non-urban roads), 0.6% (urban roads) PM: 0.1% reduction (non-motorway non-urban roads), 0.0% (urban roads) **Traffic signal priority request by designated vehicles (TSP)** The total improvement in fuel consumption and CO_2 emissions was therefore estimated as 8.28% across all buses in urban environments Total improvement in NOx and PM emissions were estimated at 8.04% and 8.17% respectively across all buses in urban environments. For CO and VOC emissions, these were assumed to be proportional to fuel consumption savings, and therefore estimated at an 8.28% reduction for urban buses. 1. Traffic information and smart routing (SmartR) 1.95% impact on fuel consumption/CO_2 emissions for passenger and freight vehicles across all road types NOx: 0.4% reduction on motorways, 1.7% reduction on non-motorway non-urban roads, 0.5% reduction on urban roads PM: 0.3% reduction on motorways, 0.8% reduction on non-motorway non-urban roads, 0.1% reduction on urban roads CO: 0.2% reduction on motorways, 4.2% reduction on non-motorway non-urban roads, 2.3% reduction on urban roads VOCs: 0.1% increase on motorways, 6.5% reduction on non-motorway non-urban roads, 1.7% reduction on urban roads
Assessment reliability of results	For the overall results of scenario E it is stated that: “It should be noted that the outputs discussed in this section are based on a modelling exercise that builds on a large consultation exercise and data collection from a variety of sources.”
Transferability of results	Assumptions are in place to distinguish between different locations/countries, such as defining frontrunners.
Scalability of results	In the study it is assumed that the results can scale up to EU level.
Feasibility assessment of use cases	-

AERIS-applications for the environment

Source reference	**AERIS-applications for the environment: real-time information synthesis**: eco-signal operations modeling report and eco-lanes operational scenario modeling report (No. FHWA-JPO-14-185 and No. FHWA-JPO-14-186). United States. Department of Transportation. Intelligent Transportation Systems Joint Program Office.
Use cases mentioned	Eco-Signal Operations: uses connected vehicle technologies and applications, as well as signal operational communications technologies, to reduce fuel consumption, greenhouse gas (GHG) and criteria air pollutant emissions on signalized arterial roadways. The applications within the scenario are designed to reduce idling, stop-and-go behavior, and inefficient accelerations and decelerations and to improve traffic flow at signalized intersections. The communication is facilitated by Dedicated Short Range Communication (DSRC) systems. On-board equipment and roadside equipment. The Operational Scenario contains several applications: Eco-Approach and Departure at Signalized Intersections, Eco-Traffic Signal Timing, Eco-Traffic Signal Priority (Freight and Transit), Connected Eco-Driving. The Eco-Lanes Operational Scenario uses CV technologies and applications to reduce fuel consumption, greenhouse gas (GHG), and criteria air pollutant emissions on dedicated freeway lanes called “eco-lanes.” The applications within the scenario are designed to reduce inter-vehicle spacing, stop-and-go behavior, and inefficient accelerations and decelerations as well as improve traffic flow along freeways. The Operational Scenario contains several applications, including Eco-Lanes Management, Eco-Speed Harmonization (ESH), Eco-Cooperative Adaptive Cruise Control (Eco-CACC), Eco-Ramp Metering, Connected Eco-Driving, and Eco-Traveler Information. Dynamic Low Emissions zones includes a geographically defined area (i.e., cordon) which seeks to restrict or deter access by specific categories of high-polluting vehicles within the zone, for the purpose of improving the air quality within the geographic area. Connected vehicle technology would be leveraged to dynamically determine fees for vehicles entering the low emissions zone. The fee for entering the low emissions zone could be based on the vehicle's engine emissions standard or historical emissions data collected directly from the vehicle using V2I communications; the driving patterns exhibited by the driver; and by air quality predictions for the zone. Using connected vehicle technologies, low emissions zone applications allow for geo-fencing of the cordon. This allows the low emissions zone to be dynamic, popping up

	based on various criteria including atmospheric conditions, weather conditions, or special events. Composed by the following applications: Connected Eco-Driving, Dynamic Emissions Pricing, Electronic Toll Collection (ETC) and Multi-Modal Traveler Information.
Region	○ El Camino Real: Palo Alto to Mountain View corridor, Northern California, USA
Method applied for obtaining impacts	Traffic Simulation Modelling: Microsimulation network (corridor-type), with 27 intersections, 6.5 mile (El Camino Real between Palo Alto and Mountain View) (Paramics), with emissions estimation tool (MOVES)
Impacts found	**Eco-Signal Operations:** **Eco-Approach and Departure at Signalized Intersections Application**: 5-10% fuel reduction benefits for an uncoordinated corridor; Up to 13% fuel reduction benefits for a coordinated corridor (8% of the benefit is attributable to signal coordination; 5% attributable to the application) **Eco-Traffic Signal Timing:** Up to 5% fuel reduction benefits at full connected vehicle penetration (5% fuel reduction benefits when optimizing for the environment (e.g., CO2); 2% fuel reduction benefits when optimizing for mobility (e.g., delay)) **Eco-Traffic Signal Priority:** up to 2% fuel reduction benefits for transit vehicles; up to 4% fuel reduction benefits for freight vehicles. **Connected Eco-Driving:** Up to 2% fuel reduction benefits at full connected vehicle penetration; Up to 2% dis-benefit in mobility due to smoother and slower accelerations to meet environmental optimums. ***Eco-Signal Operations Combined Modeling Results:*** *Up to 11% improvement in CO2 and fuel consumption at full connected vehicle penetration* **Eco-Lanes Operations:** The benefits provided by the Eco Speed Harmonization application largely depend on the situation and area in which it is being implemented (up to 4.5% fuel savings). Results up to 19% fuel savings on a real-world freeway corridor for all vehicles for ECACC and up to 22% for combination of the services. **Low emissions zones management**: Up to 2.5% reduction in fuel consumption with only eco-vehicle incentives offered. Up to 4.5% reduction in fuel consumption with both eco-vehicle incentives and transit incentives to non-eco vehicle drivers.
Assessment reliability of results	El Camino Real is a corridor with little traffic from the side-streets, which could influence the results. More configurations should be studied.
Transferability of results	Similar results may be expected in different corridors, as an extensive sensitivity analysis is carried out with different fleet mixes, different combinations of services, and different levels

	of congestions. In these sensitivity analyses, no conflicting elements that nullify effects were found.
Scalability of results	Eco-Signal Operations are useful for implementation, both in early stages of connected vehicles on-board and roadside equipment being available, as well as full availability.
Feasibility assessment of use cases	-

Predictive Cruise Control: Utilizing upcoming traffic signal information for improving fuel economy and reducing trip time

Source reference	**Predictive cruise control: Utilizing upcoming traffic signal information for improving fuel economy and reducing trip time**. Asadi, B., & Vahidi, A. (2010). IEEE transactions on control systems technology, 19(3), 707-714.
Use cases mentioned	Predictive Cruise Control (PCC) for minimizing idle time at (and braking for) traffic lights
Region	Different corridor networks, for instance Greenville, SC, USA
Method applied for obtaining impacts	Three example simulation studies. Optimization-based control algorithm that uses short range radar and traffic signal information predictively to schedule an optimum velocity trajectory for the vehicle. A. Single Vehicle scenario: Case I – Suburban driving Case II – City driving B. Multi-vehicle scenario
Impacts found	In one example case study, predictive use of signal timing reduced fuel consumption by 47% and lowered CO emissions by 36% for simulated driving through a sequence of 9 traffic lights
Assessment reliability of results	The simulation results promise that signal-to-vehicle communication technology may also enable reduction of fuel consumption, greenhouse gas emissions, and trip time of future vehicles by predictive velocity planning. Promising, but simulation is not yet elaborate enough to assess whether this works in a real-world implementation.
Transferability of results	Only three example studies are performed, more research is needed to study the effects under different traffic lights and vehicle parameters.
Scalability of results	To be studied in further research.
Feasibility assessment of use cases	-

Influences on energy savings of heavy trucks using cooperative adaptive cruise control

Source reference	**Influences on energy savings of heavy trucks using cooperative adaptive cruise control.** McAuliffe, B., Lammert, M., Lu, X. Y., Shladover, S., Surcel, M. D., & Kailas, A. (2018). (No. 2018-01-1181). SAE Technical Paper.
Use cases mentioned	Heavy-duty truck platooning (ACC for leader, CACC for followers)
Region	Test track, Transport Canada's Motor Vehicle Test Centre (MVTC) in Blainville, Quebec, Canada
Method applied for obtaining impacts	Three heavy-duty tractor-trailer trucks on a closed test track. The first truck was always in ACC mode, and the followers were in CACC mode using wireless vehicle-vehicle communication to augment their radar sensor data to enable safe and accurate vehicle following at short gaps. The fuel consumption for each truck in the CACC string was measured using the SAE J1321 procedure while travelling at 65 mph and loaded to a gross weight of 65,000 lb., demonstrating the effects of: inter-vehicle gaps (ranging from 3.0 s or 87 m to 0.14 s or 4 m, covering a much wider range than previously reported tests), cut-in and cut-out maneuvers by other vehicles, speed variations, the use of mismatched vehicles (standard trailers mixed with aerodynamic trailers with boat tails and side skirts), and the presence of a passenger vehicle ahead of the platoon.
Impacts found	Energy savings generally increased in a non-linear fashion as the gap was reduced. The middle truck saved the most fuel at gaps shorter than 12 m and the trailing truck saved the most at longer gaps, while lead truck saved the least at all gaps. The fuel-consumption savings on the curves was less than on the straight sections Driving speed at 105 km/h. Gap distance from 87m (3.0 s time gap) to 4m (0.14s time gap) Lead truck: 10% at 4m, no measurable reduction above 20m gap. Middle truck: 17% at 4m, decreasing to 6% at 87m Trailing truck: largest fuel savings of 13% at 12-17m, 11% at 4m and 8% at 87m. Maximum fuel savings of 13% at 4m. A three-truck scenario has higher fuel savings (2% higher or more) than two-truck scenario.
Assessment reliability of results	Repeatability of the setup and test procedures was verified by repeating three configurations of the three-truck CACC configuration from the previous test campaign. For cases with separation distances longer than 30 m, the previous test data were re-evaluated using the lead vehicle as the control data set for consistency with the current analysis procedures. Good agreement was found for all three vehicles at all three

	separation distances, with overlap of the confidence intervals for all fuel-savings values. These results serve as a validation that the three-truck platoon was behaving in a similar manner to the previous year's test campaign. Also studied the influence of other configurations, curves in the track, other shapes trucks and speed variations. Larger benefits may be realized on typical road geometries with limited road curvature.
Transferability of results	Results can be expected in real traffic situations. Potential added uncertainty in the calculated fuel-savings measurements associated with the use of different tractors for the control and test vehicles.
Scalability of results	Influence of other road traffic is studied: periodic cut-ins between the trucks shows no appreciable change in fuel savings (at 25m).
Feasibility assessment of use cases	Although SAE Type II testing of truck platoons has become common practice to investigate energy savings of various truck-platooning scenarios, the current study introduced considerations not previously investigated. The novel investigations of the current study include the controlled vehicle cut-ins and speed variations, the mismatched trailer parings, and the use of fuel-injector data to identify differences in fuel savings on the straight and cured segments of the track. Furthermore, this test campaign significantly expanded knowledge of performance both at closer (down to 4 m) and further (out to 87 m) following distances than any previous tests performed at vehicle speeds of 105 km/h (65 mph). These data are intended to provide some context for fuel savings to be realized under operating conditions on public roadways and in real traffic scenarios.

Impact on Congestion and Fuel Consumption of a Cooperative Adaptive Cruise Control System with Lane-Level Position Estimation

Source reference	**Impact on Congestion and Fuel Consumption of a Cooperative Adaptive Cruise Control System with Lane-Level Position Estimation.** Edgar Talavera, Alberto Díaz-Álvarez, Felipe Jiménez and José E. Naranjo (2018).
Use cases mentioned	(V2X) onboard communications – CACC solution with the help of previous road mapping. In addition, the cut-in and cut-out maneuvers for a CACC platoon are considered.
Region	Madrid corridor.
Method applied for obtaining impacts	Real environment with instrumented vehicles: Three vehicles (Mitsubishi iMiev) equipped with V2X communication DSRC-INSIA modules and Trimble R4 GNSS were used. Simulations: Simulation of Urban Mobility (SUMO). The designed system bases its operation on several elements: an accurate digital map at the lane level of the road, a

	communications system that supports the CACC, and an algorithm of positioning in the lane and decision algorithms of the CACC, designed for the optimal positioning of the vehicle as well as its correct interaction and operability.
Impacts found	The proposed CACC model does not maintain any real-time record of vehicle consumption, nor does it consider the immediate consumption of the vehicle in its decisions. Fuel consumption: low flow, system disabled: 0.064mL/veh, system disabled: 0.043 mL/veh (-33%); high flow, system disabled: 0.061mL/veh, system disabled: 0.051 mL/veh (-15%).
Assessment reliability of results	The communications are oriented to the integration of cooperative autonomous driving and the tests in real environments allow for assessment of effectiveness and versatility in different situations. V2Xcommunications allow the incorporation of warnings and information from the infrastructure, as shown by way of example in the simulations with a blocked lane. This type of messages reduces congestion and speeds up traffic by reducing fuel consumption and polluting emissions. As has been demonstrated in the tests, the CACC system improves the response because it is able to warn the drivers in advance of situations that the vehicle cannot yet detect (~500 m) with the existing sensors.
Transferability of results	-
Scalability of results	To show the potential of the system in a larger-scale implementation, simulations of the behavior are provided under dense traffic conditions where the positive impact on the reduction of traffic congestion and fuel consumption is appreciated.
Feasibility assessment of use cases	-