FINAL REPORT FOR 5GAA

# SOCIO-ECONOMIC BENEFITS OF CELLULAR V2X

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# 1 Executive summary

This is the final report of a study conducted by Analysys Mason and SBD Automotive on behalf of the 5G Automotive Association (5GAA)[1].

The overall purpose of the study has been to assess the socio-economic benefits of cellular vehicle to everything (C-V2X) technology for delivery of vehicle to everything (V2X) communication, with a focus on the benefits of such solutions in Europe.

Within the study we have examined qualitative evidence, and performed quantitative cost–benefit analysis, relating to deployment of C-V2X. Our quantitative analysis is focused on the European market, where the European Commission (EC) is currently undertaking a public consultation on deployment of cooperative intelligent transport systems (C-ITS).

## 1.1 Background and context

V2X will enable communication between vehicles, and between vehicles and infrastructure. It will potentially complement on-board sensors by providing enhanced information (such as data from other vehicles) over a longer range.

C-V2X is a technology developed by the Third Generation Partnership Project (3GPP) to deliver V2X services, using two modes of communication:

- a direct vehicle-to-vehicle mode (called ‘PC5’ in 3GPP specifications) and
- a network communications interface (called ‘Uu’ in 3GPP specifications) for vehicle-to-network (V2N) communication via existing mobile networks.

PC5 does not require mobile network assistance, but instead uses direct-mode communication between vehicles, whereas Uu communication uses existing cellular infrastructure and, in future, will use 5G networks.

Important features of C-V2X include the technology, its deployment, synergies between the two modes of C-V2X communication, and its integration with cellular technology (i.e. with existing and future mobile networks). The evolution path from C-V2X towards 5G is established as part of the 3GPP specifications, which will enable C-V2X communications to progress seamlessly into the 5G era (while offering backward compatibility with earlier C-V2X solutions).

A key reason for these C-V2X developments is to meet demand within the automotive sector for automated driving technologies. Such technologies are evolving rapidly and are widely expected to

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[1] According to its mission statement, the 5GAA defines itself as a “cross-industry association between the cellular and automotive industries to develop, test and promote communications solutions, initiate their standardisation and accelerate their commercial availability and global market penetration, to address society’s connected mobility and road safety needs with applications such as automated driving, ubiquitous access to services and integration into smart city and intelligent transportation”.

transform driving experiences, provide safer cars and improve the efficiency of car travel. In this context, the availability of advanced driver-assist systems (ADAS) (using technologies such as sensors, cameras and radar) has increased in recent years, to improve vehicle safety.[2] V2X communication is expected to complement and expand the capabilities of ADAS, and provide additional benefits (such as reduced traffic congestion, improved energy efficiency and lower vehicle emissions).

There is also an existing, short-range, wireless technology that has been standardised for V2V and vehicle-to-roadside infrastructure (V2I) connectivity, based on IEEE 802.11p. These standards have been developed over the past decade, although applications based on IEEE 802.11p have not seen widespread adoption to date.

Both C-V2X and IEEE 802.11p technologies have the potential to bring safety and efficiency benefits to transport. However, using currently defined Long-Term Evolution (LTE) technology for V2V communication, combined with LTE cellular networks for V2N, has the potential to bring additional benefits, including:

- better coverage for V2N, by exploiting existing cellular network coverage provided using lower-frequency spectrum
- reduced infrastructure deployment costs and improved service reliability, by using existing mobile infrastructure, and thus leveraging cellular technology integration and economies of scale, rather than building independently operated roadside infrastructure
- the potential for V2X and other telematics services in vehicles (e.g. infotainment) to be provided via a common cellular interface
- increased deployment flexibility, including the ability to provide coverage for both short-range and wide-area applications
- the opportunity for integration with smart-city and other connected-transportation initiatives that also use cellular technology
- enhanced security, through use of mobile subscriber identity module (SIM) cards
- certainty of future evolution to 5G, facilitating earlier deployment and after-market deployment.

## 1.2 Qualitative benefits of C-V2X, and of 5G

In future, self-driving cars will enable drivers and passengers to watch TV, listen to music, play games or access information (maps, routes, parking, traffic, news, etc.) in real time, while the vehicle is in automated driving mode. 5G is expected to further extend vehicle automation, both inside vehicles, between vehicles and with other infrastructure (e.g. mobile networks connecting smart cities, homes, offices and public services).

Various published studies refer to expectations that this ubiquitous mobile connectivity will support a wide range of societal benefits. Enabling V2X and 5G connectivity in vehicles is also expected to create new employment opportunities and support continued growth of the small and medium-sized

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[2] See https://cdn.euroncap.com/media/30599/euroncap-roadmap2025.pdf

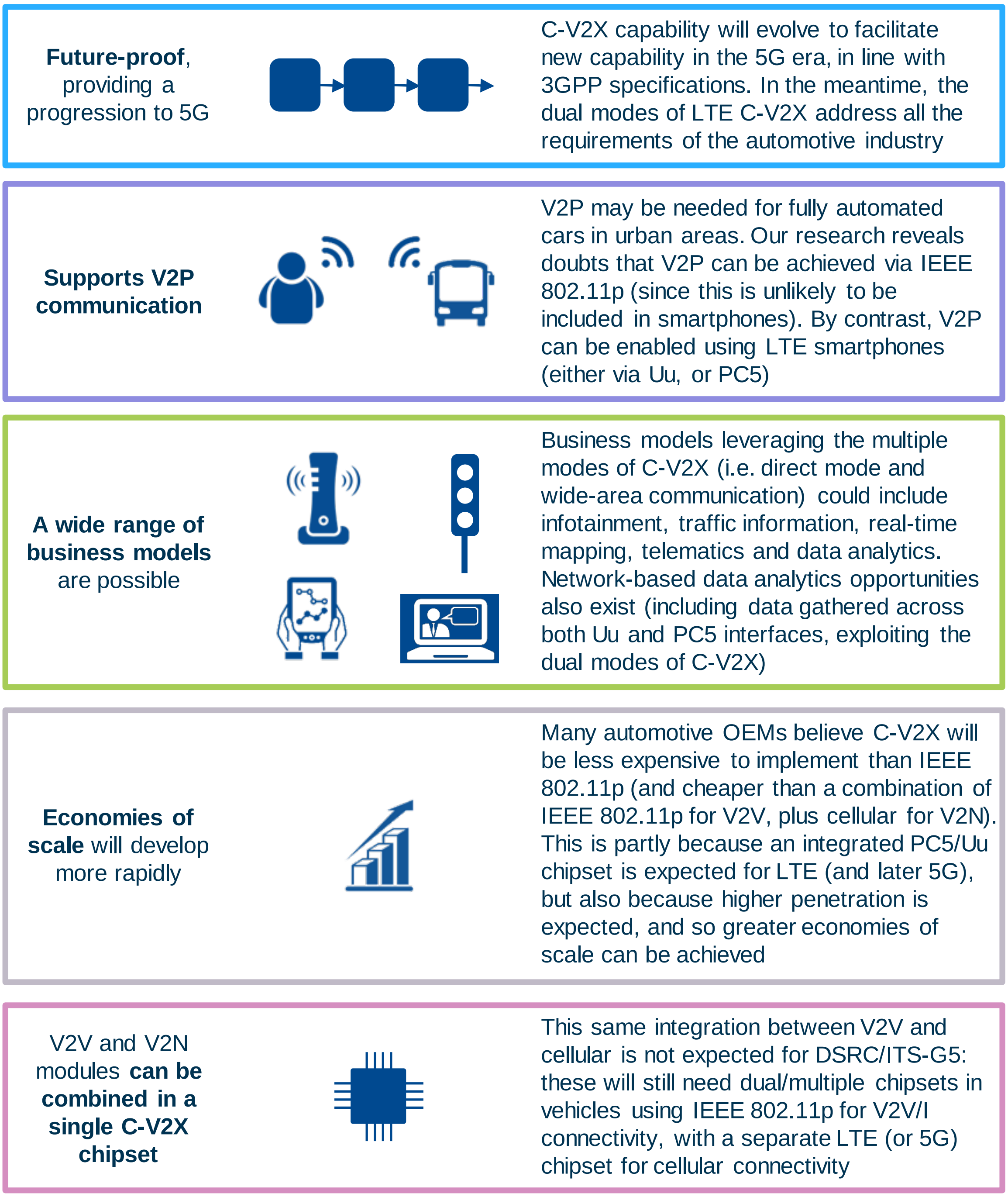
enterprise (SME) market (e.g. through opportunities for new business concepts based on new technologies, support for a greater diversity of working environments and the potential for new collaborations and partnerships).

In broad terms, the evolution from current mobile network technology to 5G new radio (5G-NR) is expected to result in significant increases in network capacity, lower latency, improved reliability and availability that together will enhance the services delivered over traditional cellular networks. 3GPP’s roadmap for future specifications also envisages enhancing the LTE PC5 communications mode, to 5G.

As part of this study, we have conducted primary research to elicit views from the mobile and automotive industries on the benefits of C-V2X. We held one-to-one interviews with companies involved in the 5GAA, including: AT&T, Audi, BMW, China Mobile, Daimler, Denso Automotive, Ericsson, Ford, Huawei, Intel, LG Innotek, Nokia, NTT DOCOMO, Qualcomm, SAIC, Samsung, Vodafone and Volkswagen. We would like to sincerely thank these companies for their inputs.

These interviews identified several key benefits, as summarised in Figure 1.1 below.

*Figure 1.1: Overview of C-V2X benefits identified by our research [Source: Analysys Mason, 2017]*



| | |
|---|---|
| **Future-proof**, providing a progression to 5G | C-V2X capability will evolve to facilitate new capability in the 5G era, in line with 3GPP specifications. In the meantime, the dual modes of LTE C-V2X address all the requirements of the automotive industry |
| **Supports V2P communication** | V2P may be needed for fully automated cars in urban areas. Our research reveals doubts that V2P can be achieved via IEEE 802.11p (since this is unlikely to be included in smartphones). By contrast, V2P can be enabled using LTE smartphones (either via Uu, or PC5) |
| **A wide range of business models** are possible | Business models leveraging the multiple modes of C-V2X (i.e. direct mode and wide-area communication) could include infotainment, traffic information, real-time mapping, telematics and data analytics. Network-based data analytics opportunities also exist (including data gathered across both Uu and PC5 interfaces, exploiting the dual modes of C-V2X) |
| **Economies of scale** will develop more rapidly | Many automotive OEMs believe C-V2X will be less expensive to implement than IEEE 802.11p (and cheaper than a combination of IEEE 802.11p for V2V, plus cellular for V2N). This is partly because an integrated PC5/Uu chipset is expected for LTE (and later 5G), but also because higher penetration is expected, and so greater economies of scale can be achieved |
| V2V and V2N modules **can be combined in a single C-V2X chipset** | This same integration between V2V and cellular is not expected for DSRC/ITS-G5: these will still need dual/multiple chipsets in vehicles using IEEE 802.11p for V2V/I connectivity, with a separate LTE (or 5G) chipset for cellular connectivity |

## 1.3 Quantitative benefits

As part of the study we defined four scenarios to help us quantify changes in the magnitude of the overall costs and benefits associated with different timescales and volumes of V2X adoption. We also wanted to distinguish relative differences in the net benefits, depending on whether LTE/4G PC5 and forthcoming 5G PC5 or IEEE 802.11p technology is adopted in vehicles, and the extent to which synergies with cellular networks are exploited for provision of V2I/vehicle to pedestrian (V2P).

A summary of the scenarios we modelled is provided in Figure 1.2 below:

*Figure 1.2: Summary of scenarios for quantitative analysis [Source: Analysys Mason, 2017]*

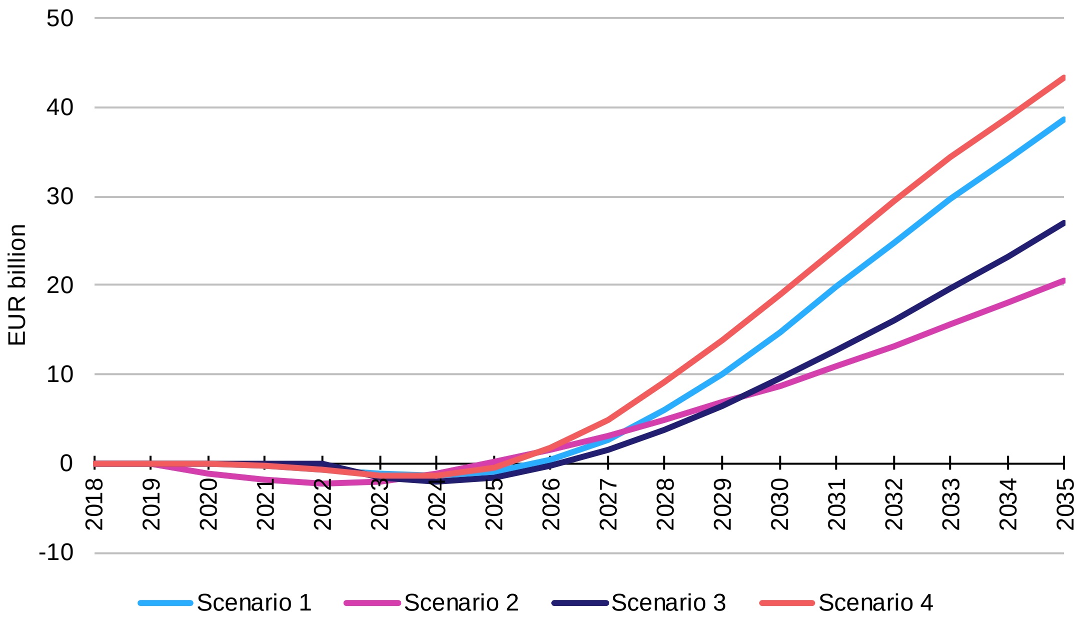
| Scenario | Summary | Net benefits in 2035 |
|---|---|---|
| **1 – Base case** | Adoption and timing of deployment is determined by automotive original equipment manufacturers (OEMs), in the absence of any regulatory measures | EUR39 billion |
| **2 – 2020 EC mandate on V2V/V2I** | An EC mandate requiring all new vehicle models to support EC-defined 'Day 1' and 'Day 1.5' services from 2020 results in C-ITS services using IEEE 802.11p technology for V2V and V2I. Provision of V2I using IEEE 802.11p requires extensive roll-out of 5.9GHz roadside units (RSUs) | EUR20 billion |
| **3 – 2023 EC mandate on V2V/V2I** | An EC mandate requiring all new vehicle models to support 'Day 1' and 'Day 1.5' services from 2023 results in C-ITS services using LTE PC5 technology for V2V and V2I. Provision of V2I using PC5 requires extensive roll-out of 5.9GHz RSUs | EUR27 billion |
| **4 – Equitable 5.9GHz use** | C-V2X and IEEE 802.11p technologies co-exist in 5.9GHz spectrum, with an equitable division of spectrum enabling adoption of both technologies based on market demand | EUR43 billion |

The highest net benefits at the end of the modelling period (2035) – EUR43 billion – come from the equitable 5.9GHz use scenario, followed closely by the base case (EUR39 billion). The 2023 EC mandate on V2V/V2I scenario generates around EUR27 billion of monetised benefits, resulting from lower benefits and higher costs compared to the equitable 5.9GHz use and the base case, while the high costs and relatively lower benefits of the 2020 mandate on V2V/V2I scenario suggest it will generate lower net benefits than all other scenarios (EUR20 billion).

## 1.4 Conclusions and recommendations

The research conducted for this study, combined with our modelling results, suggests that the deployment of C-ITS systems is beneficial at the European Union (EU) level. Net benefits that could be accrued in Europe are estimated to be in the range of EUR20 billion to EUR43 billion in 2035, across the four scenarios modelled (see Figure 1.3).

*Figure 1.3: Evolution of net benefits, by scenario [Source: Analysys Mason, 2017]*



Several conclusions can be drawn from the modelling results:

- ***Most benefits are expected to be generated from increased road safety and traffic efficiency***. The largest contributors to monetised benefits are a reduction in time spent on the road (i.e. due to less time being wasted in traffic, which represents 80% of benefits generated in 2035 in Scenario 1) and a reduction in accident rates (17% of benefits in Scenario 1). Together, they account for over 97% of total benefits generated in Scenario 1, while the benefits from reduced fuel consumption and $CO_2$ emissions are negligible.

- ***The base case and equitable 5.9GHz use scenarios (without an EC mandate requiring 5.9GHz roadside unit (RSU) deployment, and encouraging PC5-based V2V take-up), appear to be the most beneficial way to deploy C-V2X services, from a net benefit perspective.*** Although Scenarios 2 and 3 achieve positive net benefits in the long run, the investment required to upgrade roadside infrastructure with 5.9GHz RSUs means it takes longer to achieve breakeven than in Scenarios 1 and 4, where the re-use of cellular networks to provide V2N reduces costs significantly, and also allows high infrastructure penetration from day 1 (resulting in benefits from V2I/V2N services being realised sooner).

- ***Additional benefits from C-V2X can be achieved if LTE PC5 communication is integrated into future smartphones.*** In Scenarios 1, 3 and 4, the ability for vehicles without an embedded PC5 or IEEE 802.11p interface to access V2I/V2P communications via a smartphone can lead to further increases in both the penetration, the unitary benefit per vehicle and the overall benefits generated.

- ***Most costs are expected to be incurred by in-vehicle C-ITS systems***. In Scenarios 2 and 3, the requirement for all new vehicle models to have C-ITS systems means that in-vehicle costs account for over 85% of cumulative costs over the modelling period, with the remaining costs being related to the roll-out of PC5/IEEE 802.11p-based RSUs in existing roadside infrastructure. It is noted that any regulatory requirement to support interoperability between IEEE 802.11p and PC5-based systems would increase in-vehicle costs further. For example, if an automotive OEM that wished to equip a vehicle with V2V communications needed to install both PC5 and IEEE 802.11p for interoperability reasons, the in-vehicle costs would be significantly increased. This is due to the additional radio frequency components (i.e. chipsets and antennas), as well as the increased cost of integrating both solutions into vehicle telematic or other control units, since it is not technologically feasible for the two V2V radio systems (IEEE 802.11p and C-V2X PC5) to communicate with each other.[3] Our view, based upon research for this study, is that the additional costs of supporting dual technologies for V2V to provide interoperability between all vehicles would be high relative to the available evidence on the benefits that would be gained.

We have also identified the following recommendations:

- **European C-ITS policy should support synergies between the two modes of C-V2X communication, and with the wider ecosystem of 3GPP-based infrastructure.** The two modes of C-V2X communication offer a potential for technology integration between V2V/V2I and existing cellular networks (i.e. using V2N), with resulting cost–benefit advantages. There is also potential to use V2N in C-V2X over existing mobile network infrastructure, and avoid the need for additional RSU deployment for V2I in some cases. This could reduce costs and would allow higher infrastructure penetration from service launch, compared to a scenario in which V2I services rely on extensive RSU roll-out.

- **Migration towards 5G-based V2X should be encouraged, in line with market demand.** The migration from 4G to 5G technology will take some time to implement, but should provide a significant capacity increase and improved network flexibility. This future evolution path provides backward compatibility with previous generations of 3GPP technology, and is a key benefit of C-V2X.

- **V2P services deployed as part of C-V2X can provide additional benefits.** Most respondents to our primary research for this study thought it was unlikely that IEEE 802.11p chipsets will be integrated into smartphones in future. In contrast, they expressed more positive views that smartphones can be C-V2X-enabled, creating an opportunity for V2P services, as well as enabling vehicles without embedded C-V2X communication to use C-V2X smartphones (i.e. ‘after-market devices’, in our analysis). V2P will benefit several categories of road user, including pedestrians, cyclists and motorcyclists. V2P will also be essential for vehicles to be fully automated on urban roads (e.g. to identify when to stop at a non-signalised crossing if a pedestrian is approaching).

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[3] A mandate from the Radio Spectrum Committee (RSC) to the Conference of Postal and Telecommunication Administrations (CEPT) in October 2017 to study extension of the ITS-safety related spectrum at 5.9GHz recognises that the two V2V systems (IEEE 802.11p and C-V2X PC5) cannot communicate with each other.

# 2 Introduction

This is the final report of a study conducted by Analysys Mason and SBD Automotive on behalf of the 5G Automotive Association (5GAA)[4] to analyse the net benefits of cellular vehicle-to-everything (C-V2X) wireless technology within vehicle-to-everything (V2X) communication. V2X will potentially extend the communication range between vehicles, and between vehicles and infrastructure, as compared to the use of on-board sensors in vehicles. V2X will improve road safety and traffic efficiency, and provide environmental benefits, as well as enabling new services to be offered.

The purpose of the study has been to examine qualitative evidence, and perform quantitative analysis, regarding the net benefits of C-V2X. Quantitative analysis is focused on the European market, where the European Commission (EC) is currently undertaking a public consultation on deployment of cooperative intelligent transport systems (C-ITS).

### 2.1.1 Overview of C-V2X

C-V2X involves vehicles exchanging messaging and data with one another and with cellular infrastructure, and was recently specified by the Third Generation Partnership Project (3GPP) – the industry's specification body for mobile communications technologies – in its Release 14 specifications. The Release 14 specifications define C-V2X communication using LTE-based direct communications (termed 'PC5' in 3GPP specifications for vehicle to vehicle/infrastructure, or V2V/V2I) as well as network communication (termed 'Uu' in 3GPP specifications for vehicle to network, or V2N). In due course, 3GPP specifications will evolve to use new 5G radio technology (5G-NR).

C-V2X communication can be used in combination with other connected-vehicle technology, such as sensors, radar and cameras, to assist cars in automated or semi-automated driving modes. C-V2X comprises two transmission modes – vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications using spectrum in the 5.9GHz band, and vehicle-to-network (V2N) communication using existing licensed mobile spectrum. The former mode of communication does not require mobile network assistance, whereas the latter can use existing cellular infrastructure and, in future, will use 5G networks.

There is also an existing, short-range, wireless technology standardised for V2V and vehicle-to-roadside infrastructure (V2I) connectivity, based on IEEE 802.11p. These standards have been developed over the past decade, although applications based on IEEE 802.11p have not seen widespread adoption to date. As a result, there are now two technologies in place for V2V/V2I and associated vehicle-to-pedestrian (V2P) services, and alternative options for deploying the V2N transmission.

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[4] According to its mission statement, the 5GAA defines itself as a cross-industry association between the cellular and automotive industries to "develop, test and promote communications solutions, initiate their standardization and accelerate their commercial availability and global market penetration to address society's connected mobility and road safety needs with applications such as autonomous driving, ubiquitous access to services and integration into smart city and intelligent transportation".

Both C-V2X and IEEE 802.11p technologies have the potential to bring safety and efficiency benefits to transport. However, using currently defined LTE technology for V2V communication, combined with LTE cellular networks for V2N, has the potential to bring additional benefits, including:

- better coverage for V2N, by exploiting existing cellular network coverage provided using lower-frequency spectrum
- reduced infrastructure deployment costs and improved service reliability, by using existing mobile infrastructure, and thus leveraging cellular technology integration and economies of scale, rather than building independently operated roadside infrastructure
- the potential for V2X and other telematics services in vehicles (e.g. infotainment) to be provided via a common cellular interface
- increased deployment flexibility
- the opportunity for integration with smart-city and other connected-transportation initiatives that also use cellular technology
- enhanced security, through the use of mobile subscriber identity module (SIM) cards
- certainty of future evolution to 5G.

In particular, 5G technologies are expected to deliver additional performance benefits (e.g. mission-critical low-latency requirements) as well as an expanded range of telematics and infotainment services, both for connected and automated driving (potentially enabling full autonomy in cars), as well as providing additional, real-time, connected infotainment services within vehicles.[5]

## 2.2 Background and context for the study

*Evolution of cellular technology, and the role of C-V2X and 5G in automated and connected vehicles*

The mobile industry is working with several vertical industry sectors, including the automotive sector, to prepare specifications for next-generation, ultra-high-speed wireless connectivity. Mobile networks are expected to evolve to provide higher-speed, lower-latency 4G services and capabilities, as well as introducing new 5G radio technology and virtualised core networks. 5G networks are being designed to seamlessly support a diverse range of connected devices, services and industries, taking the potential use cases for mobile infrastructure significantly beyond today’s consumer-driven mobile broadband services, and towards high-speed, ultra-reliable connectivity for multiple industries that might use mobile networks for wireless connectivity, between people, places and things. Policy makers worldwide are recognising the potential for 5G within a future digital economy and society.

The 3GPP has already prepared updates to the latest 4G specifications (Long-Term Evolution Advanced, or LTE-A), as well as embarking on a preliminary specification phase for 5G. The intention is that initial 5G specifications will be developed by 2018, with leading mobile network operators (MNOs) beginning 5G deployments from 2018 onwards.

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[5] See https://ec.europa.eu/info/consultations/public-consultation-specifications-cooperative-intelligent-transport-systems_en

The EC has developed a '5G Action Plan' for the European Union (EU),[6] which estimates that benefits from 5G deployment in Europe could reach EUR113 billion annually by 2025.[7] The EC's study identifies three capabilities of 5G that will drive future benefits: ultra-high data speeds; scalable, future-proof solutions for sensor and other networks within the Internet of Things (IoT); and ultra-responsive connectivity for future real-time applications. Four industrial uses of 5G networks are highlighted as contributing to the forecast future benefits – healthcare, automotive, transport and utilities – with a large portion of strategic benefits (EUR13.8 billion annually) derived from services in the automotive sector.

The mobile and automotive industries widely expect that 5G will facilitate the delivery of connected and automated driving solutions with high mobility and lower latency, enabling real-time communication between cars over harmonised licensed mobile spectrum (i.e. for V2N using existing mobile networks) as well as using licence-exempt 5.9GHz spectrum designated for Intelligent Transport System (ITS) V2V/V2I use. In addition to what current C-V2X will deliver, the bandwidth offered by 5G will enable richer data exchange with vehicles, including real-time maps, connected infotainment and additional audiovisual entertainment.[8]

Ahead of 5G deployment, the mobile and automotive industries are preparing for V2X communication using new LTE-based direct communications (PC5) complemented by existing LTE/4G communication. The latest 3GPP specifications for LTE/4G incorporate new V2X capabilities, including V2V and V2N communication, as well as communication between vehicles and vulnerable road users (e.g. vehicle to pedestrian (or V2P) and vehicle to cyclist) that does not require a mobile network connection.

A key reason for these developments is to meet demand within the automotive sector for automated driving technologies. Such technologies are evolving rapidly and are widely expected to transform driving experiences, provide safer cars and improve the efficiency of car travel. In this context, the availability of advanced driver-assist systems (ADAS) (using technologies such as sensors, cameras and radar) has increased in recent years, to improve vehicle safety.[9] V2X communication is expected to complement and expand the capabilities of ADAS, and provide additional benefits (such as reduced traffic congestion, improved energy efficiency and lower vehicle emissions).

### *Policy drivers for connected and automated vehicles*

Many policy makers, including those in Europe, are expecting connected vehicles – and potentially fully automated ones – to be in widespread use over the coming decade. The number of cars with embedded connectivity is already growing rapidly, as illustrated in Figure 2.1 below.

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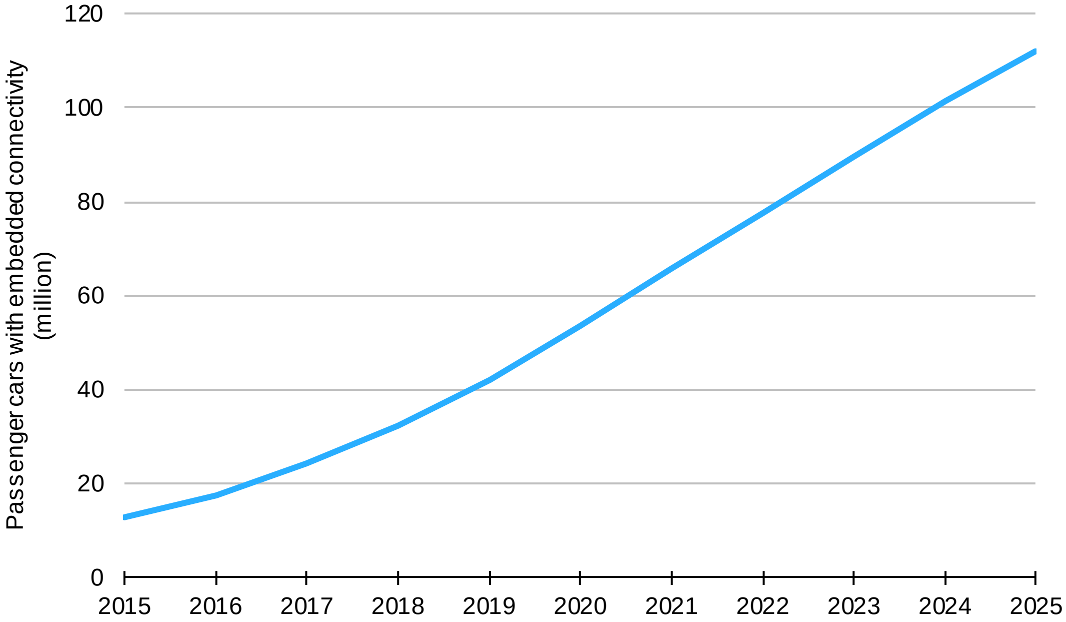
[6] *5G for Europe: An Action Plan*, communication from the EC to the European Parliament and others (published on 14 September 2016).

[7] See http://www.telecomengine.com/benefits-from-5g-in-europe-estimated-to-reach-e113-1bn-annually-by-2025/

[8] See https://www.vodafone.com/content/dam/vodafone-images/public-policy/reports/pdf/gigabit-society-5g-14032017.pdf

[9] See https://cdn.euroncap.com/media/30599/euroncap-roadmap2025.pdf

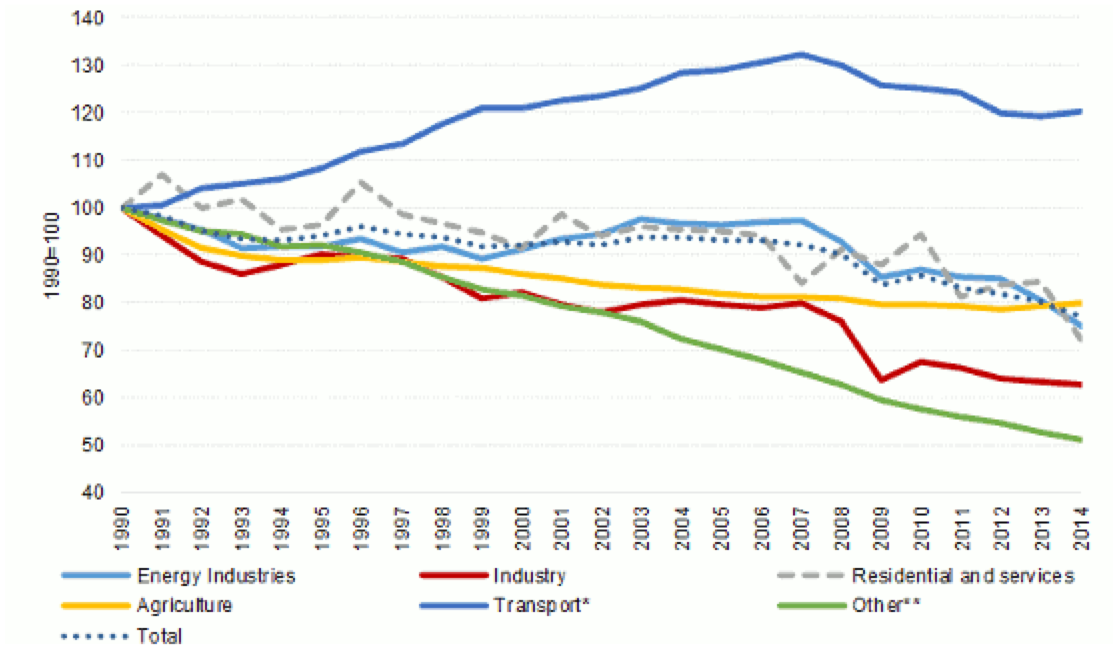
*Figure 2.1: Passenger cars with embedded cellular connectivity in EU Member States, 2015–2025 [Source: Analysys Mason, 2017]*



Connected vehicles are expected to contribute to improved road safety, higher efficiency of road transport and reduced vehicle emissions.

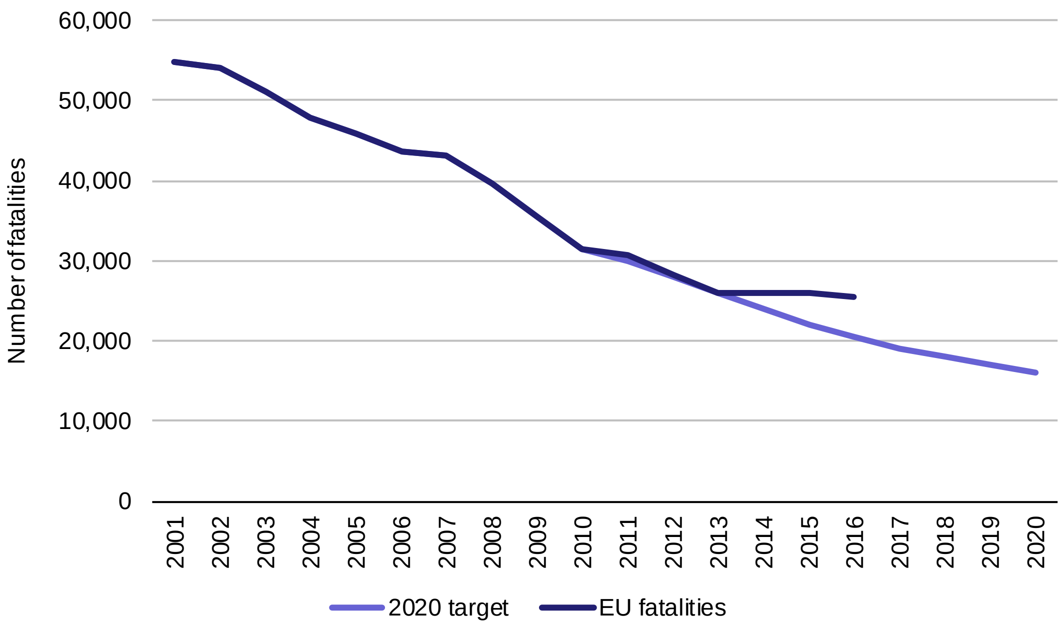
For example, increasing road use in the EU has been a key driver of increased traffic congestion, higher energy consumption and worsening pollution over the past 20 years. The transport sector is one of only a few sectors that have not seen the same gradual decline in $CO_2$ emissions as other sectors (e.g. agriculture, industry). Emissions have been in decline since 2007, but are still at a higher level than in 1990, as indicated by Figure 2.2.

*Figure 2.2: Evolution of $CO_2$ emissions (1990=100) [Source: European Commission, 2017]*



While the number of fatalities on roads fell by more than 23% between 2010 and 2016[10] (from 31 500 in 2010 to 25 500 in 2016), the decline has been stagnating since 2013 and may be insufficient for the EU to meets its target of halving road fatalities between 2010 and 2020, as indicated by Figure 2.3.

*Figure 2.3: EU road fatalities and targets, 2001–2020 [Source: EU Community Road Accident Database,[11] 2017]*



In this context, the development of C-ITS[12] is expected to play a key role in improving road safety and traffic efficiency, and in reducing fuel consumption and $CO_2$ emissions.

In 2016, a European strategy on C-ITS was published, setting out priorities for the deployment of C-ITS, with a goal of services being introduced by 2019.[13] The strategy drew on results of cost–benefit analysis[14] to assess the costs and benefits associated with the deployment of C-ITS services across the EU. At that time, the technology being specified to provide C-ITS services in Europe was based on the IEEE 802.11p standard, although using cellular infrastructure for V2I (rather than deploying dedicated roadside infrastructure) was recognised as a means of accelerating infrastructure penetration across all roads from the very first launch of C-ITS services, thus ensuring that the full capability of V2X can be achieved.[15] Since then, the mobile industry has developed

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[10] See http://europa.eu/rapid/press-release_IP-17-674_en.htm

[11] See http://europa.eu/rapid/press-release_MEMO-17-675_en.htm

[12] In a move to facilitate the deployment of C-ITS in Europe, the EC decided in 2014 to set up a cooperative framework (‘C-ITS platform’) including national authorities, C-ITS stakeholders and the EC to develop a common vision on the interoperable development of C-ITS across the EU, and identify the most likely and suitable deployment scenarios.

[13] See https://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v5.pdf

[14] See https://ec.europa.eu/transport/sites/transport/files/themes/its/doc/c-its-platform-final-report-january-2016.pdf

[15] For example, a conclusion on page 43 of the *Study of deployment of C-ITS in Europe: Final Report* prepared by Ricardo Energy & Environment for EC DG MOVE in 2016 is that “Using cellular networks to provide V2I services can have immediate benefits” (see https://ec.europa.eu/transport/sites/transport/files/2016-c-its-deployment-study-final-report.pdf).

C-V2X specifications within Release 14 of the 3GPP specifications for LTE/4G, in the expectation that 5G-based C-V2X will be analysed in 3GPP specifications from Release 16 onwards (initial 5G deployment, providing enhanced mobile broadband services, will be specified in Release 15).

As a result of these developments, there are now two technologies suitable for the provision of C-ITS in Europe, and many other global regions:

- **IEEE 802.11p-based** technology is specified to provide V2V and V2I communication, using low-power technology operating in 5.9GHz spectrum. V2I using IEEE 802.11p communication would be achieved by deploying low-power roadside units (RSUs) at traffic junctions and along transport routes.
- **C-V2X** is also specified to provide V2V communication using LTE-based technology in 5.9GHz spectrum. For V2I or V2N, C-V2X can either use existing cellular infrastructure and the associated licensed spectrum that cellular networks use today, or it can use roadside infrastructure over 5.9GHz spectrum. As the cellular industry evolves to 5G, C-V2X is also expected to evolve to use new 5G direct-mode communication and 5G networks.

## 2.3 Scope of study and approach

*Study scope*

The overall purpose of the study has been to assess the benefits of C-V2X technology for delivery of V2X communication, with a focus on the benefits of such solutions in Europe.

The overall scope of work was as follows:

- To develop a cost–benefit model incorporating a series of modelling scenarios to quantify the impact on overall benefits of alternative market penetration assumptions for C-V2X, compared to alternative solutions (i.e. IEEE 802.11p)
- To gather primary research on C-V2X deployment plans, technology benefits and business cases, based on telephone interviews with 5GAA members,[16] as well as a selection of other companies involved in C-ITS developments more broadly
- To present qualitative evidence on the potential benefits of using C-V2X technologies, including migration to 5G, the services supported, case studies of trials to date and other relevant qualitative evidence.

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[16] A full list of 5GAA members can be found at http://5gaa.org/

*Approach*

Our approach to the study combined secondary research with quantitative modelling and primary research conducted using telephone interviews and questionnaires issued to 5GAA member companies:

- We reviewed previous published studies and other relevant literature to develop an initial qualitative assessment of C-V2X developments, including market opportunity, challenges and policy implications in the EU.
- We developed an initial cost–benefit model to quantify the costs and benefits of deploying C-ITS systems in the EU up to 2035
- We conducted interviews with nearly 25 5GAA members
- We used the information obtained during the interviews to inform our modelling assumptions, validate our initial understanding of C-V2X developments, and define a series of modelling scenarios based on alternative penetration assumptions for C-V2X and IEEE 802.11p.

## 2.4 Structure of this report

The remainder of this document is laid out as follows:

- Section 3 summarises market developments relating to connected and automated driving
- Section 4 provides an overview of C-V2X
- Section 5 describes the analysis conducted for this study to quantify the costs and benefits of C-V2X
- Section 6 sets out our conclusions and recommendations.

There are also three annexes containing supplementary material:

- Annex A provides a summary of abbreviations and acronyms used in the report
- Annex B includes a fuller description of the modelling approach
- Annex C summarises the primary research conducted during the study.

# 3 Market developments relating to connected and automated driving

In this section we provide an overview of C-ITS services (including developments in connected and automated vehicles and their expected benefits), an overview of the key technologies and policy developments, a description of mobile network evolution to 5G, as well as examples of C-V2X deployments and trials to date.

## 3.1 Overview of C-ITS

### *C-ITS services*

The concept of connected and automated driving has been around for more than 20 years.[17] General Motors (GM) was the first automotive manufacturer to introduce connected-car features, when it launched 'OnStar'[18] in 1996. The primary purpose of OnStar was safety, and to get emergency help to a vehicle following an accident. Remote diagnostics were introduced as a service in connected cars in 2001. By 2003, connected car services included vehicle health reports, turn-by-turn directions and a network access device. Data-only telematics were first offered in 2007.

ADAS were first introduced by automotive manufacturers (also referred to as automotive other equipment manufacturers (automotive OEMs)) in Europe in 1998, providing an adaptive cruise-control feature. Since then, numerous other ADAS have been introduced by automotive manufacturers, involving a combination of sensors and proprietary solutions. Many of the collision-avoidance features (e.g. advanced emergency braking, or AEB) are now being included as standard on new vehicles.

In 2014, Audi was the first automotive manufacturer to offer 4G LTE Wi-Fi hotspot access, and the first mass deployment of 4G LTE was by General Motors in the same year.

While ADAS are growing in maturity, their reliance on on-board sensors limits their range of action and capabilities (e.g. automotive sensors have a design requirement of around 200 metres, in perfect weather and line-of-sight conditions, although depending on the object detected (e.g. pedestrians, cyclists) in practice the range can be a lot smaller). Also, since ADAS sensors are line-of-sight devices, they cannot sense objects that are obstructed by road furniture or other vehicles. In this context, the near-future opportunity for vehicles to interact with one another and with road infrastructure using wireless communications is widely recognised as a way to expand the range and capabilities of connected cars (and to support higher levels of autonomy in vehicles). Such developments are referred to as V2X communication.

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[17] For example, the National Automated Highway System Consortium (NAHSC) project was initiated in the USA in 1994 and the European PROMOTE-Chauffeur was an early project in the EU around 2000.

[18] See https://www.onstar.com/us/en/home.html

In general, the automotive industry expects V2X to expand the range of these systems and bring significant improvements in not only road safety, but also traffic efficiency, fuel consumption and pollution emissions, among others. However, how V2X will be deployed – including the technologies to be used, and the infrastructure needed for communication with roadside networks – has been under discussion for some time.

The idea of deploying C-ITS communications services in Europe was introduced in CEN/TC 278,[19] then adopted by ERTICO-ITS Europe,[20] a platform for cooperation among industry stakeholders (including mobile operators, public authorities, automotive OEMs and vendors). ERTICO-ITS Europe defines C-ITS as a subset of intelligent transport systems (ITS). C-ITS communication involves ITS stations (e.g. roadside infrastructure, vehicles, traffic control centres, mobile devices) communicating and sharing information to provide "increased road safety, traffic efficiency, comfort and sustainability benefits to road users than standalone ITS stations".[21]

C-ITS services are commonly categorised into one of four types:

- ***V2V services*** rely on the exchange of data between two vehicles in proximity of each other. The exchange of data is primarily broadcast-based. A roadside unit may be used as a repeater forwarding node to extend the range of transmission between vehicles. V2V services are expected to be primarily used for safety-related benefits (e.g. reducing collisions between vehicles). This mode typically does not rely on network infrastructure.

- ***V2I services*** rely on the exchange of data between a vehicle and an RSU, often connected to roadside infrastructure (e.g. traffic signals, variable message signs), or between a vehicle and a locally relevant application server, via a local area wireless network. V2I services provide direct information to vehicles and are expected to increase road safety (e.g. roadworks warnings), improve traffic efficiency (e.g. navigation, parking) and reduce energy consumption / pollution.

- ***V2P services*** rely on the exchange of data between a pedestrian and a nearby vehicle. Similar to V2V services, V2P services are expected to be primarily used for safety reasons.

- ***V2N services*** rely on the exchange of data between a vehicle and application server using a wide-area network. An RSU may be used as a repeater / forwarding node to extend the range of transmission of the signal received from a vehicle. V2N services are expected to increase road safety (e.g. eCall) and traffic efficiency (e.g. navigation) and improve the comfort of passengers (e.g. video and music streaming, internet browsing). Vehicle-to-grid (V2G) connectivity might also be added (e.g. for managing electricity generation to support the demand for electric vehicles).

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[19] See https://ec.europa.eu/transport/sites/transport/files/themes/its/events/doc/2012-06-07-workshop/2.2-cen-tc-278-wg16.pdf

[20] See http://ertico.com/vision-and-mission/

[21] See http://www.cvt-project.ir/Admin/Files/eventAttachments/Guide-about-technologies-for-future-C-ITS-services-v1-0-2%202015_605.pdf

Figure 3.1 below provides an illustration of the different types of C-ITS service.

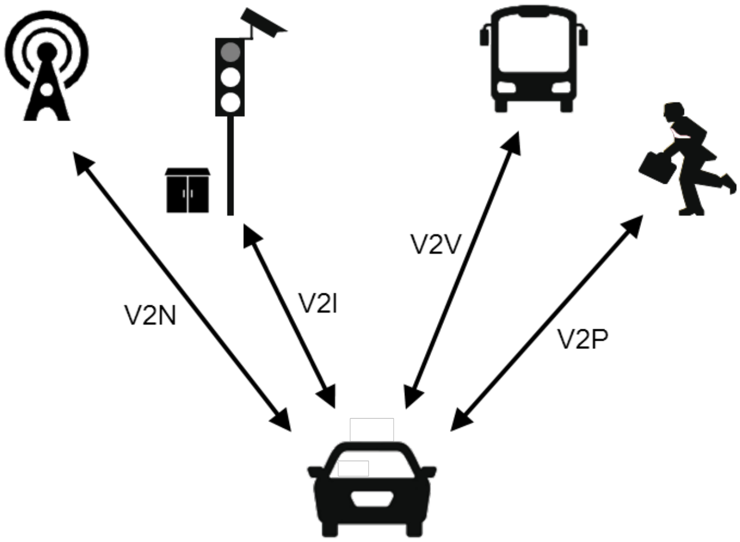

*Figure 3.1: Overview of V2X communication types [Source: Analysys Mason, 2017]*

*Use cases*

The number of use cases for C-ITS is potentially significant. The ‘Platform for the Deployment of Cooperative Intelligent Transport Systems in the European Union’ (C-ITS Platform) defined 25 highly beneficial services for priority deployment, in an attempt to provide a common framework to increase the speed of deployment of C-ITS, the interoperability of services, and geographical continuity of services across EU Member States. In the C-ITS Platform it is envisaged that these services (summarised in Figure 3.2 below) will be deployed quickly, so that end users and society enjoy the benefits as soon as possible.

*Figure 3.2: Key priority C-ITS services defined by the C-ITS Platform [Source: Analysys Mason, 2017]*

| **V2V services** | **V2I services** | **V2P services** |
|---|---|---|
| • Emergency electronic brake light<br>• Emergency vehicle approaching<br>• Slow or stationary vehicles<br>• Traffic jam ahead warning<br>• Hazardous location notification<br>• Roadworks warning<br>• Shockwave damping<br>• Cooperative collision warning<br>• Motorcycle approaching indication | • Weather conditions<br>• In-vehicle signage<br>• In-vehicle speed limits<br>• Probe vehicle data<br>• Green light optimal speed advisory (GLOSA)<br>• Signal violation / intersection safety<br>• Traffic signal priority requested by designated vehicles<br>• On-street parking management<br>• Off-street parking management<br>• Park & ride information<br>• Information on fuelling & charging stations for alternative fuel vehicles<br>• Traffic information and Smart routing<br>• Zone access control for urban areas<br>• Loading zone management<br>• Wrong way driving | • Vulnerable road user protection |

Other highly beneficial V2X services commonly referred to as leading towards fully automated driving include ‘do not pass’ warnings, active braking and cooperative adaptive cruise control (CACC).

More broadly, there is potential for a range of connected mobility services to be provided in vehicles, beyond the road-safety services that are the focus of C-ITS. Connected mobility services refers to the range of mobile data services that are consumed on smartphones and other connected devices today. These include internet browsing, audiovisual entertainment, cloud-based applications and live television (TV) and radio services that today’s connected citizens access on mobile devices.

In future, connected cars equipped with 5G will provide drivers and passengers with the ability to watch TV, listen to music, play games or access information (maps, routes, parking, traffic, news, etc.) in real time. 5G is expected to extend the automation of communications connectivity in vehicles, between vehicles and with other infrastructure (e.g. mobile networks connecting smart cities, homes, offices and public services).

Various published studies refer to expectations that this ubiquitous mobile connectivity will support a wide range of societal benefits. Enabling V2X and 5G connectivity in vehicles is also expected to create new employment opportunities and support continued growth of the small and medium-sized enterprise (SME) market (e.g. through opportunities for new business concepts from new technologies, support for a greater diversity of working environments and the potential for new collaborations and partnerships). These benefits are summarised in Figure 3.3 below.[22]

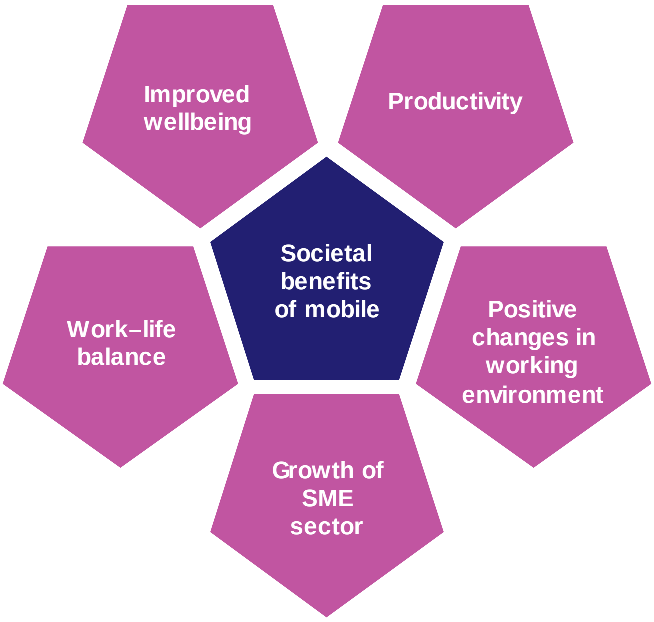

*Figure 3.3: Societal benefits of ubiquitous mobile connectivity [Source: Analysys Mason, 2017]*

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[22] For example, see the *GSMA Mobile Connectivity Index* (https://www.gsma.com/mobilefordevelopment/programme/connected-society/gsma-launches-mobile-connectivity-index), the Euro-5G project (https://5g-ppp.eu/euro-5g/) and *The rise of mobile in a connected society* (O2, 2015) (https://news.o2.co.uk/wp-content/uploads/2015/03/The-rise-of-mobile-in-a-connected-society-Booklet-FINAL.pdf)

*Quantifying C-ITS benefits*

C-ITS systems are expected to bring socio-economic benefits, particularly in the form of road safety, traffic efficiency, fuel consumption and pollution emissions.

Most of the quantifiable benefits of C-ITS are generated from the potential for fewer accidents, along with improved productivity (e.g. reduced driving times), better efficiency and reduced emissions:

- A 2016 study[23] conducted by Ricardo Energy & Environment on behalf of the EC estimated that the net benefits of deploying C-ITS services in the EU could reach between EUR4 billion and EUR13 billion in 2030, based on deploying bundles of C-ITS services. The study assessed five categories of impact (road safety, fuel consumption, $CO_2$ emissions, CO/NOx/VOC/PM emissions and traffic efficiency). The 'high' sensitivity estimated that the net benefits could reach EUR17.3 billion in 2030. The largest share of benefits was generated by the reduction in accidents.

- The US Department of Transportation published a notice of proposed rulemaking (NPRM) on connected-vehicle technology in 2017, which referred to significant benefits from mandating C-ITS in terms of crashes prevented, lives saved, injuries prevented and damaged vehicles spared.[24]

Studies also identify a wide range of other industries that will benefit from increased use of connected and automated vehicles, including insurance, transportation, logistics and retail, as well as the telecoms and associated industries (such as electronics and IT). Environmental and societal benefits will also be created – particularly a reduction in noise and pollution, and contribution to work–life balance.

A study conducted for the EC on socio-economic benefits from 5G introduction in the EU[25] estimates that across the four industrial sectors studied (automotive, healthcare, transport and utilities) the benefits of 5G introduction might reach EUR62.5 billion in 2025. A large proportion of these benefits are attributed to the automotive sector.

A study[26] conducted by KPMG in March 2015 on behalf of the UK-based Society of Motor Manufacturers and Traders (SMMT) estimated that the overall economic benefits of connected and automated vehicles in the UK could reach GBP51 billion in 2030. The largest share of benefits is expected to be generated from a direct improvement in travel conditions for consumers, which in turns will create wider benefits, including fewer accidents (more than 25 000 accidents prevented and in excess of 2500 lives saved over 2014–2030), improved productivity and increased trade (more than 320 000 additional jobs created over 2014–2030). Overall, the KPMG study expects these benefits to increase the UK's GDP by more than 1% in 2030.

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[23] See https://ec.europa.eu/transport/sites/transport/files/2016-c-its-deployment-study-final-report.pdf

[24] See https://www.its.dot.gov/index.htm

[25] See https://ec.europa.eu/digital-single-market/en/news/5g-deployment-could-bring-millions-jobs-and-billions-euros-benefits-study-finds

[26] See https://www.smmt.co.uk/wp-content/uploads/sites/2/CRT036586F-Connected-and-Autonomous-Vehicles-%E2%80%93-The-UK-Economic-Opportu...1.pdf

In this context, policy makers in many leading markets worldwide have been considering the regulatory measures needed to develop and exploit connected and automated vehicle communications technologies. Section 3.2 discusses these developments in more detail.

## 3.2 C-ITS technologies, and policy developments

*C-ITS technologies*

As discussed above, C-ITS services envisage the exchange of data between two (or more) vehicles (V2V), from nearby roadside infrastructure or networks to vehicles (V2I or V2N), and between pedestrians and vehicles (V2P).

By nature, these services have different range and latency requirements, which in turn translate into different technology needs. For example, V2V, V2I and V2P services involve communication over a short distance (e.g. up to 300m for most applications), require low latency and, for many applications, high reliability (e.g. cooperative collision warning services). By contrast, V2N services involve communication over a remotely located application server, but also require high availability.

V2X technologies can be categorised into short-range and wide-area technologies:

*Short-range technologies*

Low-powered technologies using the 5.9GHz spectrum are designed to meet the short-range, high-availability and high-reliability requirements of V2V and V2I services (with V2I provided through deployment of dedicated low-power RSUs along transport routes and at junctions).

Key short-range radio technologies available include IEEE 802.11p (for which initial standards were completed in 2014[27] in Europe) and LTE direct mode (or ‘PC5’, for which the initial, 3GPP Release 14 specification was completed in 2017). Both radio technologies operate in the 5.9GHz spectrum allocated in Europe, the USA, Korea (and soon in China) for ITS communications. Another short-range technology is ITS Connect, a proprietary solution deployed by Toyota in Japan over a dedicated 9MHz band in the 760MHz spectrum (755.5–764.5MHz).[28]

In the USA, IEEE 802.11p is known as WAVE (Wireless Access for Vehicular Environments) or DSRC (Dedicated Short-Range Communications). In Europe, IEEE 802.11p formed the basis for the ETSI ITS-G5 standard for ITS systems, and it can use the 5.9GHz (5855–5925MHz) spectrum allocated by the EC for C-ITS communications.

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[27] See http://www.etsi.org/news-events/news/753-2014-02-joint-news-cen-and-etsi-deliver-first-set-of-standards-for-cooperative-intelligent-transport-systems-c-its

[28] See https://docbox.etsi.org/Workshop/2015/201503_ITSWORKSHOP/SESSION03_CITS_BEYONDRELEASE1/ITSCONNECTPROMOTION_SHIBASAKI.pdf

*Wide-area technologies*

Wide-area technologies refer to cellular technology used in mobile networks, over spectrum licensed to mobile operators, and are best suited for the requirements of V2N services. As the adoption of C-ITS is expected to be sensitive to costs, cellular technologies are likely to offer deployment benefits, given the widespread coverage and availability of 4G cellular networks, and the potential for evolution to 5G. In the C-V2X specifications, V2N communication is referred to as ‘Uu’, and updated specifications were completed in 3GPP Release 14 in June 2017.

A key benefit of C-V2X is its future evolution path (and backward compatibility with previous generations of 3GPP technology). Release 15 of the 3GPP specification (anticipated to be finalised by September 2018) will introduce 5G-NR in cellular networks focused on mobile broadband services, and Release 16 (expected in 2019) is set to include 5G-NR C-V2X. Release 16 will include consideration of 5G direct-mode communication, and a candidate for short-range technologies at 5.9GHz.

The IEEE 802.11p standard has been in place for some time, but with limited adoption. Some automotive OEMs have held trials or announced plans to adopt IEEE 802.11p technology in vehicles:

- ***General Motors***. In 2017, GM equipped its new Cadillac CTS cars with V2V services based on IEEE 802.11p technology. In May 2017, Cadillac conducted demonstrations in the USA to show IEEE 802.11p-based V2I communications between vehicles and traffic signals.

- ***Volkswagen***. From 2019, Volkswagen has said that it plans to equip selected new vehicle types with IEEE 802.11p capabilities as a standard feature, as well as providing embedded cellular connectivity.

Cellular technology has also been widely adopted in vehicles for some time. Since GM launched OnStar in 1996, and the introduction of the eCall regulation in 1999 (adopted in 2015), the automotive industry has moved to equip all vehicles with cellular connectivity, as well as increasing levels of automation and communication.

Examples of automotive OEMs which have implemented pre-Release 14 LTE (V2N) in vehicles are as follows:

- ***BMW Connected Drive***. BMW’s first ‘connected car’ offering was launched in 2001 and enabled rapid access to information for in-car use from its BMW Online portal. In 2008, it was the first automotive OEM to allow unlimited in-car internet usage. Since 2015, all new BMW cars have been equipped with the ‘BMW Connected Drive’ range of connected-car services. Standard features of BMW Connected Drive include access to vehicle information and remote-control features via a smartphone application. Additional premium features include real-time traffic information, concierge services, remote ‘personal assistant’ services and infotainment services.

- ***Mercedes me***. Mercedes-Benz started fitting most of its new car models with embedded cellular connectivity in September 2014, and offers a suite of services (e.g. navigation, infotainment, remote customer support) through its ‘Mercedes me connect’ subscription service. The ‘Mercedes me’ application also provides information and basic controls that can be accessed via a mobile device.

*C-ITS policy developments*

Policy makers in many countries worldwide have been preparing policies on C-ITS for some time, reflecting the fact that technologies for cooperative driving are evolving, and automated vehicles are being introduced in the market. Work is still ongoing in the areas of security/privacy, conformance, public awareness and economic sustainability, since these kinds of deployment require involvement from state, regional and local governments and road authorities.

► *Europe*

In Europe, the digitalisation of transport and the use of intelligent transport systems (ITS) has generated growing interest from the EC, due to the potential to increase road safety, address emission and traffic congestion issues, and support jobs and economic growth in the transport sector. Back in August 2008, the EC published Decision 2008/671/EC to designate the frequency band 5875–5905MHz for safety-related applications of ITS, and adopted the ITS Action Plan (COM (2008) 886[29]), which included targeted initiatives to accelerate and coordinate the deployment of ITS systems in road transport in the EU. In July 2010, a legal framework (Directive 2010/40/EU[30]) was adopted to accelerate the deployment of ITS across Europe, with the V2I link defined as a key priority area.

In November 2014, the EC launched the C-ITS Deployment Platform, a cooperative framework involving national authorities, C-ITS stakeholders (not including the mobile sector) and the EC to identify the remaining barriers and propose solutions for the deployment of C-ITS systems in the EU.

The first phase of the C-ITS Platform (2014–2016) focused on the development of a common vision on the interoperable deployment of C-ITS systems in the EU, including the identification of key technical, legal and commercial issues and the development of policy recommendations to address these issues. The first phase ended with publication of an expert report in January 2016,[31] complemented by a cost–benefit analysis[32] and a public consultation.[33]

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[29] See http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52008DC0886&from=EN

[30] See http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0040&from=EN

[31] See https://ec.europa.eu/transport/sites/transport/files/themes/its/doc/c-its-platform-final-report-january-2016.pdf

[32] See https://ec.europa.eu/transport/sites/transport/files/2016-c-its-deployment-study-final-report.pdf

[33] See https://ec.europa.eu/transport/sites/transport/files/2016-c-its-deployment-study-public-consultation.pdf

The C-ITS Platform started its second phase in July 2016. The objective was to further develop a shared vision on the interoperable deployment of C-ITS systems in the EU, by defining the common technical and legal framework to address key issues on security, data protection, compliance assessment and hybrid communication identified in the first phase, and by investigating further the benefits that C-ITS will bring in terms of automation. The 5GAA attended two C-ITS Platform meetings as guests during 2017. The second phase ended with the publication of an expert report in September 2017.[34]

In parallel, the EC has adopted various other policies which are relevant for connected, cooperative and automated mobility. In particular, "5G for Europe: An Action Plan"[35] calls for the availability of 5G along main European transport paths.[36]

On 18 October 2017, the Radio Spectrum Committee (composed of the EC and representatives of regulators from EU Member States) approved a new mandate for CEPT to study an extension of the ITS-safety related spectrum band at 5.9GHz, with the possibility of extending the dedicated ITS band to 50MHz in bandwidth (from 30MHz currently). The mandate recognises recent developments in relation to LTE-based V2X specification for ITS, which could underpin the path to 5G connectivity for the automotive and road transport sectors. The mandate also recognises that the two V2V radio systems (IEEE 802.11p and C-V2X PC5) cannot communicate with each other. The mandate includes two main study requirements:

- the inclusion of urban rail in the upper part of the ITS band (5905–5925MHz), for communication-based train control, or CBTC)
- the coexistence between ITS-G5, LTE-V2X and CBTC.

CEPT is to deliver a final report on this topic by March 2019.

► *The USA*

The USA was the first country to assign spectrum in the 5.9GHz band for DSRC-based ITS services, but there has been a significant delay between this spectrum being assigned, and its being put into use. In January 2017, the US Department of Transportation (US DOT) issued a Notice of Proposed Rulemaking (NPRM)[37] to require all new light vehicles to be capable of V2V communications. It proposes to mandate IEEE 802.11p as the communication technology for V2V, and require automotive OEMs to begin implementing these requirements two years after the final rule is adopted (although with a three-year ramp-up period to accommodate automotive OEM product cycles). The NPRM did not require specific V2V safety applications to be available, but the Notice suggests that

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[34] See https://ec.europa.eu/transport/sites/transport/files/2017-09-c-its-platform-final-report.pdf

[35] See http://ec.europa.eu/newsroom/dae/document.cfm?doc_id=17131

[36] See http://ec.europa.eu/newsroom/dae/document.cfm?doc_id=41205

[37] See https://www.regulations.gov/document?D=NHTSA-2016-0126-0009

future regulations could mandate specific intersection safety applications. The NPRM attracted hundreds of responses, and the USDOT has given no indication on when it will proceed.[38]

Separately, the US DOT's Federal Highway Administration Infrastructure Deployment Guidelines were temporarily published but then withdrawn. It was anticipated that these guidelines would foster V2I communications, to help transportation planners integrate the technologies that allow vehicles to communicate with roadside infrastructure (e.g. traffic signals, stop signs in work zones).

- *China*

While no specific spectrum has been allocated for ITS services in China, the Ministry of Industry and Information Technology (MIIT) is in the process of allocating 50MHz in the 5.9GHz band for ITS systems, on a licence-exempt basis. In November 2016, the Chinese government announced the allocation of 20MHz (5905–5925MHz) for C-V2X trials in six major cities. It is possible that China will be the first country to launch C-V2X – research conducted for this study suggests that C-V2X commercial launch in China could be in the second half of 2019.

- *Japan*

In Japan, the 5.9GHz band has been used by a Japanese technology called electronic tolling collection (ETC). There are reports that this band may be considered for use to provide V2V and V2I communications, but it is unclear whether a decision will be made in the near future. In the meantime, Toyota has already deployed its proprietary "ITS Connect" solution in 12 cities. ITS Connect delivers V2V and V2I communications over a dedicated 9MHz band of 760MHz spectrum set aside by the Japanese government. ITS Connect is available on new Toyota vehicles in Japan, although to date very few traffic junctions have been equipped with the RSUs needed for V2I communications using the ITS Connect solution.

- *South Korea*

In September 2016, South Korea's Ministry of Communications allocated the 5855–5925MHz band for ITS services on a licence-exempt, technology-neutral basis.

- *Australia*

In September 2017, Australia's telecoms regulator, ACMA, closed a consultation on the allocation of 5.9GHz for ITS, proposing rules to follow a technology-neutral approach.[39]

## 3.3 Mobile network evolution to 5G

Some of the key benefits of using C-V2X to provide C-ITS services are both its dual mode of short-range and wide-area communication (using cellular infrastructure to accelerate infrastructure

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[38] Recent reports suggest that the proposed rulemaking will not proceed under the US Trump administration.

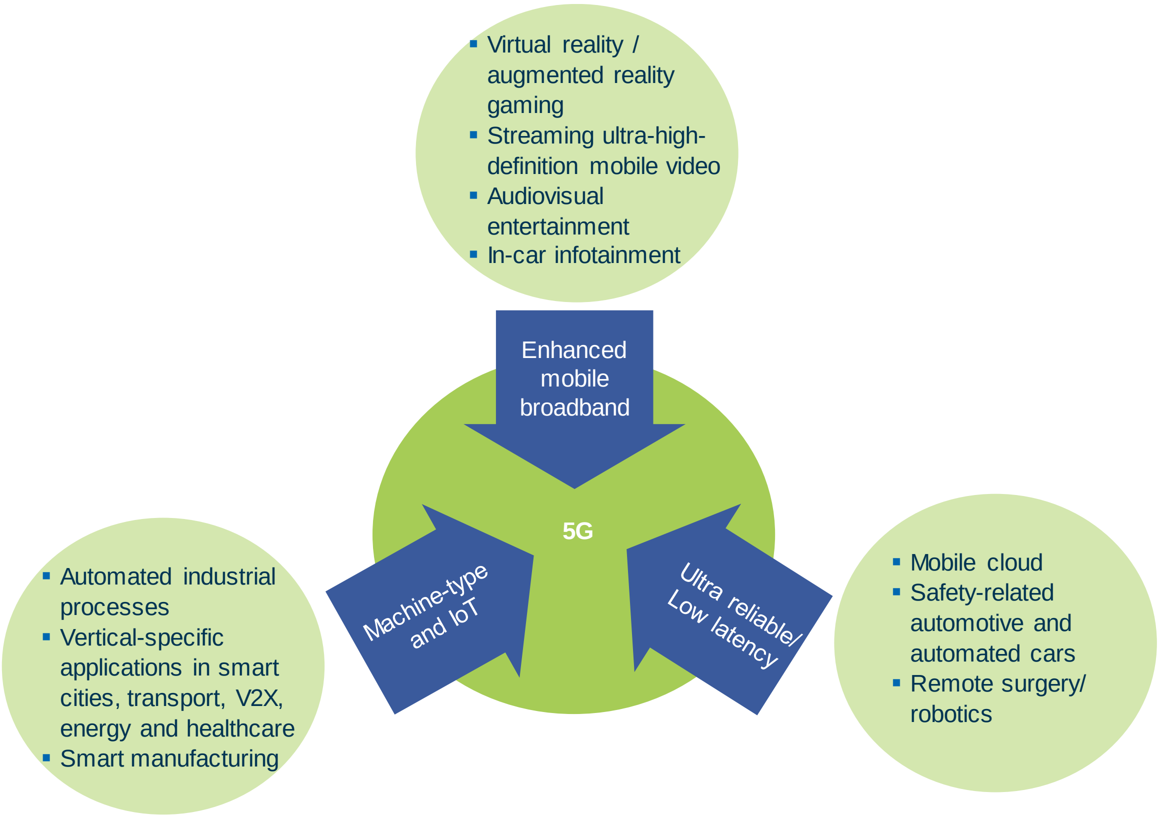
[39] See https://www.acma.gov.au/theACMA/proposed-regulatory-measures-for-the-introduction-of-c-its-in-australia

penetration, including in non-urban areas), and its future evolution path (since in due course C-V2X will take advantage of 5G technology).[40]

The path to 5G represents a significant step change in mobile network capabilities, flexibility and the range of services supported. 5G specifications are being designed to deliver consistent ultra-fast data speeds of 100Mbit/s or more, providing 'fibre-like' performance in terms of throughput, capacity, latency and reliability. 5G networks will provide connections with a latency of only a few milliseconds, and extremely high reliability. Networks are being designed to deliver services not just to mobile devices and devices within the home or office, but also to a massive number of connected things that make up the IoT. Network virtualisation and associated innovations – for example, in mobile cloud technologies – will support service delivery to different industrial users through the use of 'network slicing', to satisfy individual service needs.

In broad terms, 5G use cases will range from augmented reality and virtual reality, audiovisual entertainment, healthcare and manufacturing through to provision of infotainment and entertainment in vehicles (see Figure 3.4). C-V2X has been one of the highest-profile use cases discussed for 5G and hence the automotive industry is viewed as a key sector that will benefit from 5G capabilities and services. Release 15 of the 3GPP specifications will include 5G mobile broadband services, and 3GPP Release 16 will consider 5G direct-mode communication for C-V2X.

*Figure 3.4: 5G use cases [Source: Analysys Mason, 2017]*



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[40] Industry expectations are that 5G will be introduced in leading markets from 2020, followed by rapid deployment across many developed and developing nations from around 2025.

As part of the EC's 5G Action Plan, we note that the migration path of C-V2X technology to 5G will enable automated vehicles to benefit from the capabilities of 5G technology, and thus generate substantial socio-economic benefits, as identified in previous EC studies (e.g. as referred to in Section 3.1).

To achieve the socio-economic benefits of 5G technology deployment in the automotive sector, European C-ITS policy needs to be designed to encourage migration from current V2X technologies to 5G, and this is one of the recommendations from our study (see Section 6.2).

## 3.4 Implementing Release 14 C-V2X

With the 3GPP Release 14 specifications for C-V2X having been finalised in 2017, various trials have been announced in 2017 (e.g. in Germany, France and the USA, and others are planning trials). Trials that are now underway or planned by the automotive and telecoms industry worldwide are demonstrating V2V/V2I/V2P (PC5) performance, use cases and how the C-V2X ecosystem can be complemented by network-based transmission modes. Qualcomm was the first chipset manufacturer to announce an LTE direct-mode/PC5 chipset, which will be available from 2018.[41]

Some examples of C-V2X trials and technology demonstrations are shown in Figure 3.5 below.

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[41] See https://www.qualcomm.com/invention/technologies/lte/advanced-pro/cellular-v2x

*Figure 3.5: C-V2X trials and technology demonstrations [Source: Analysys Mason, 2017]*

| | | |
|---|---|---|
| **Deutsche Telekom (DT)**, Continental, Fraunhofer, Nokia Networks | Real-time V2N2V (<20ms latency) | Demonstrated on DT's LTE network with Mobile Edge Computing technology (Nov-15); and by Nokia Networks in China (Nov-16) |
| **Audi**, DT, Huawei, Toyota, other automotive OEMs | C-V2X | Technical LTE-based field trial (Jul-16) |
| **Audi**, Ericsson, Qualcomm, SWARCO Traffic Systems, University of Kaiserslautern | C-V2X | Formed Connected Vehicle to Everything of Tomorrow (ConVeX) consortium (Jan-17) to demonstrate C-V2X (3GPP Release 14) |
| **Ericsson**, BMW Group, Deutsche Bahn, DT, Telefónica Deutschland, Vodafone, TU Dresden 5G Lab Germany, Federal Highway Research Institute (BASt), Federal Regulatory Agency (BNetzA) | C-V2X | Formed 5G-Connected Mobility consortium (Nov-16) to develop real-world application environment for 5G-based C-V2X; uses 700MHz band on an independent 5G test network |
| **Vodafone**, Bosch, Huawei | C-V2X (direct V2V) | LTE-based trial (Feb-17); aims to demonstrate very low latency, and differences from IEEE 802.11 solutions |
| **'Towards 5G' partnership** (Ericsson, Orange, PSA Group, Qualcomm) | C-V2X | Is testing C-V2X technologies. First phase tested initial use cases (Feb-17). Will demonstrate use of a network slice to isolate C-V2X from MBB traffic. Will assess how 3GPP Release 14 can enhance C-V2X performance, and develop use cases for C-V2X and 5G |
| **UK Connected Intelligent Transport Environment (UKCITE)** (Vodafone, Jaguar LandRover) | C-V2X and IEEE 802.11p | Launched to provide a real-world testing environment for V2X (Feb-17) |
| **National Intelligent Connected Vehicle Testing Demonstration Base,** Shanghai (China Mobile Communications Corporation, SAIC Motor, Huawei) | C-V2X | Established in 2016, to test connected cars, facilitate R&D, test and certify connected-vehicle technology. Shanghai is planning an intelligent vehicle network covering 100km$^2$ |
| **Michigan,** USA (Ford Motor Company, Qualcomm) | C-V2X | Part of Connected Vehicle Safety Pilot. Ford has tested automated vehicles, with V2V based on LTE direct-mode transmission |
| **5G showcase trials,** South Korea (LG Electronics, Qualcomm) | C-V2X and IEEE 802.11p | Will trial automotive connectivity solutions on Qualcomm's connected car platform in 1H 2018; supports C-V2X (3GPP Release 14) and IEEE 802.11p |
| **San Diego,** Regional Proving Ground (AT&T, Ford, Nokia, Qualcomm, supported by the San Diego Association of Governments) | C-V2X | Will demonstrate the cost-efficient benefits of C-V2X, with embedded cellular technology in vehicles, and synergies between the deployment of cellular base stations and RSUs |

# 4 Overview of C-V2X

C-V2X technology has been developed as an advanced V2V/V2I/V2P and V2N communications standard, with connectivity delivered using new LTE-based direct-mode communication technology and existing mobile networks. Current C-V2X specifications will evolve into the 5G era with 3GPP Releases 15 and 16, ensuring that technology investment is future-proof and will support envisaged V2X use cases (from safety-related warning and information services through to full autonomy).

This section discusses the development of C-V2X technology in more depth, as well as its use cases, the expected roadmap towards C-V2X commercialisation and adoption, and the likely evolution of C-V2X penetration.

## 4.1 Technology development and use cases

Initial C-V2X technology specifications were introduced as part of 3GPP Release 14, stemming from device-to-device features first introduced in 3GPP Release 12, then adapted for automotive mobility and message size requirements. 3GPP Releases 15 and 16 are currently adding new features to the specifications. These included the specifications and service requirements (e.g. latency/reliability, message size, frequency, range, speed, security) for two modes of communication:

- ***Direct communication (PC5)***: LTE-based (and future 5G NR-based) communications via a PC5 interface without the support of a wide-area mobile network. No subscription to a mobile operator’s data plan is required under this mode. Direct communication mode supports V2V, V2I and V2P communications. 3GPP Release 14 defines a specific deployment configuration (Mode 3) whereby scheduling and interference management of V2V traffic is assisted by a cellular base station[42] via control signalling over the traditional cellular network interface (see Figure 4.1 below). In an alternative configuration (Mode 4), scheduling and interference management of V2V traffic is based on distributed algorithms between the vehicles. Both configurations use global navigation satellite systems (GNSS) for location and for time synchronisation, and for the Cooperative Awareness Message (CAM) and Decentralised Environmental Notification Message (DENM) capabilities.

- ***Mobile network communication (Uu)***: LTE-based (and future 5G NR-based) communications via mobile infrastructure. This mode of communication can typically be used for V2N communications between a vehicle and an application server, and represents the evolution and optimisation of existing cellular mobile network access. It can also be used to coordinate V2V direct communications via resources allocation managed by a mobile network.

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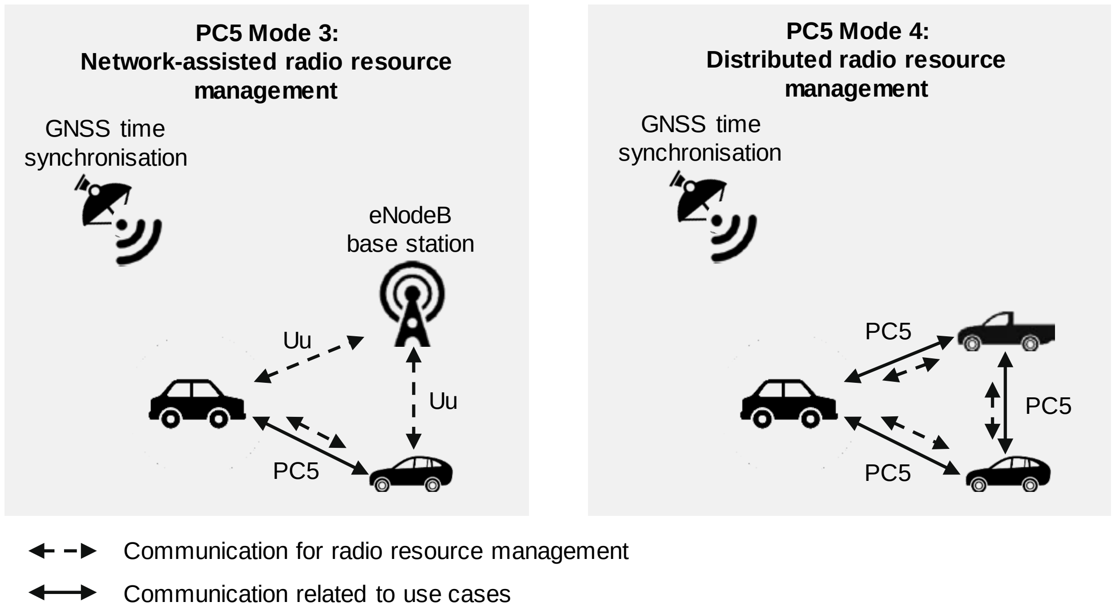
[42] Also referred to as an ‘eNodeB’.

*Figure 4.1: Overview of V2V scheduling and resources allocation by configuration [Source: Analysys Mason, 2017]*



Vehicles and road infrastructure can use both modes of communication simultaneously, i.e. they can use direct communication mode to transmit information while also receiving navigation information (for example) from a mobile network. Both modes of communication use different frequency bands (i.e. harmonised licence-exempt spectrum for ITS, and licensed mobile spectrum) and so do not compete for bandwidth.

Some of the specific use cases considered by the 3GPP when developing the technical requirements for C-V2X in 3GPP Release 14 (as defined by TS 22.185[43]) included forward collision warning, control loss warning, emergency vehicle warning, CACC, queue warning, automated parking system, vulnerable road user safety, etc., matching the use cases developed by ETSI-ITS.

One of the key benefits of C-V2X is that the technology and capabilities will evolve in line with the normal sequence of 3GPP releases. The next release will be 3GPP Release 15 (as defined by TS 22.886[44]), planned for September 2018. Release 15 will specify the new radio interface for 5G (5G-NR) for mobile broadband, as well as further evolution of LTE direct communications (PC5). More-complex use cases are considered in Release 15, including vehicle CACC, sensor and state map sharing, intersection safety information, provisioning for urban driving, etc.

Although 3GPP Release 15 will define 5G-NR for mobile broadband use, 3GPP Release 16 is expected to be the first 3GPP release that will analyse 5G-NR C-V2X capabilities. 5G-NR C-V2X is expected to enable further improvements in performance, add new capabilities (e.g. wideband carrier support, high throughput, ultra-low latency, ultra-high reliability) to connected vehicles and

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[43] See https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2989

[44] See https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3108

supporting infrastructure, and extend the number of V2X use cases (e.g. accurate positioning and ranging for high-density CACC, see-through / high-throughput sensors, sensor data sharing between vehicles, sharing of updates to high-definition (HD) maps with other vehicles on the road, ‘bird’s eye view’ of intersections). Backward compatibility between 5G-NR and LTE will mean that when 5G-NR C-V2X is introduced, new vehicles will have backward compatibility with older vehicles and infrastructure, in terms of both V2V and V2I communications.

The interviews conducted with 5GAA members for this study identified several benefits of C-V2X, as summarised in Figure 4.2 below.

*Figure 4.2: Overview of C-V2X benefits identified by our research [Source: Analysys Mason, 2017]*

| | |
|---|---|
| **Future-proof**, providing a progression to 5G | C-V2X capability will evolve to facilitate new capability in the 5G era, in line with 3GPP specifications. In the meantime, the dual modes of LTE C-V2X address all the requirements of the automotive industry |
| **Supports V2P communication** | V2P may be needed for fully automated cars in urban areas. Our research reveals doubts that V2P can be achieved via IEEE 802.11p (since this is unlikely to be included in smartphones). By contrast, V2P can be enabled using LTE smartphones (either via Uu, or PC5) |
| **A wide range of business models** are possible | Business models leveraging the multiple modes of C-V2X (i.e. direct mode and wide-area communication) could include infotainment, traffic information, real-time mapping, telematics and data analytics. Network-based data analytics opportunities also exist (including data gathered across both Uu and PC5 interfaces, exploiting the dual modes of C-V2X) |
| **Economies of scale** will develop more rapidly | Many automotive OEMs believe C-V2X will be less expensive to implement than IEEE 802.11p (and cheaper than a combination of IEEE 802.11p for V2V, plus cellular for V2N). This is partly because an integrated PC5/Uu chipset is expected for LTE (and later 5G), but also because higher penetration is expected, and so greater economies of scale can be achieved |
| V2V and V2N modules **can be combined in a single C-V2X chipset** | This same integration between V2V and cellular is not expected for DSRC/ITS-G5: these will still need dual/multiple chipsets in vehicles using IEEE 802.11p for V2V/I connectivity, with a separate LTE (or 5G) chipset for cellular connectivity |

More broadly, 5G-NR is expected to play a key role in enhancing the services delivered over traditional cellular networks, enhancing the direct communications mode, and facilitating earlier deployment by:

- supporting very high (Gbit/s) data speeds for mobile broadband, which will enable mobile broadband via very high (Gbit/s) data speeds – improving streaming services and enabling virtual reality applications, 3D HD maps, remote supervisory control, and so on
- providing new capabilities and optimising massive IoT communications, including a multi-hop mesh for increased coverage and lower-power communications
- maintaining backward compatibility with Release 14 PC5 and Uu
- evolving the PC5 direct communications interface in line with the above.

## 4.2 Roadmap towards PC5 commercialisation

For the Uu mode of C-V2X, deployment is already possible using pre-Release 14 LTE networks, and it is expected that operators will upgrade networks to support the latest Release 14 functions in line with normal network-upgrade cycles.

Initial specifications for C-V2X communications using the PC5 mode were first introduced in 3GPP Release 14. Our interviews with 5GAA members suggest the following timelines for commercial launch of this new mode of LTE communication:

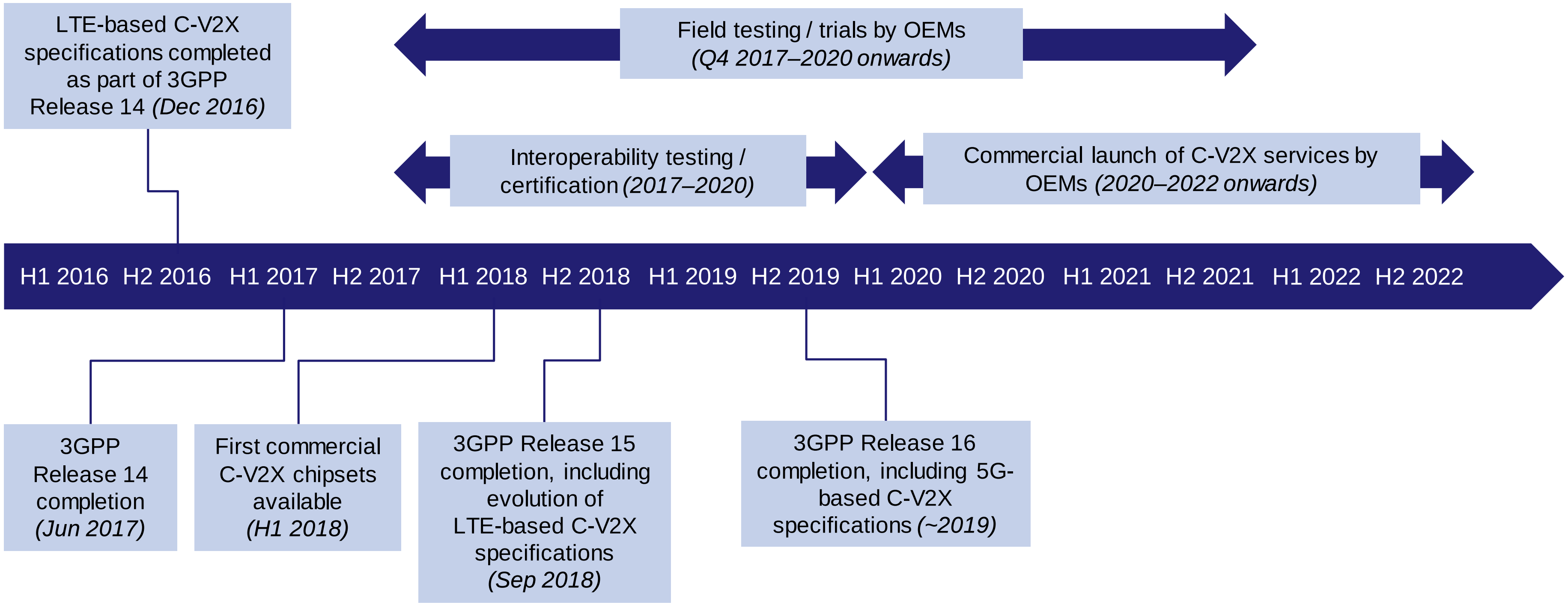
- ***Definition of standards for testing and interoperability will be completed by 2018***. Full interoperability specifications are being developed by regional standardisation bodies, including work to complete the high-level/application protocols and to integrate these with the ETSI-ITS protocol stack (in Europe).
- ***Compatibility / interoperability testing will occur in 2018–2019***. Testing requirements are being defined and planned by 5GAA Working Group 3 (evaluations, testbeds and pilots) and are expected to be ready by 2018. Testing will most likely be complete by 2019.
- ***Field testing and trials will launch in early 2018***. Automotive manufacturers are expected to start testing theoretical and real-life performance (e.g. range, reliability, interference) of C-V2X PC5 mode using pre-commercial chipsets from early 2018, and continuing until 2019/2020. A few ‘testbed’ trials are already underway: in China, for example, testing is reportedly at a more-advanced stage, because a cross-industry consortium is committed to deploying a testbed in Shanghai in 2018, possibly including a large-scale trial. A few tests are reportedly planned in Europe, but these involve individual pilots rather than a central large-scale trial.
- ***Hardware will be available by 2018***. Pre-commercial chipset prototypes are expected to be available by the end of 2017, and commercial chipsets from mid-2018 (e.g. in September 2017 Qualcomm announced that commercial chipsets would be launched in the second half of 2018).

- ***Security infrastructure will be ready by 2019***. Security infrastructure to support C-V2X PC5 is currently being defined and should be ready by mid-2018 or early 2019. Much of the work required has been completed by the EC, which will act as a central organisation to validate certificates produced by automotive OEMs. For traditional cellular connectivity, security procedures are already in place, based on the security infrastructure of existing mobile networks.

- ***Commercial launch will be in 2020–2022***. The first commercial deployment is expected to be in China – one LTE vendor mentioned a cross-industry partnership to deploy Release 14-based C-V2X in vehicles and infrastructure by 2020. In Europe, C-V2X-enabled vehicles could be expected from 2020–2022. Recent reports also suggest that a mandate stipulating IEEE 802.11p use for V2V communications is still being reviewed in the USA.

Figure 4.3 below provides a possible timeline towards commercialisation of C-V2X in Europe, based on research conducted during this study.

*Figure 4.3: Overview of C-V2X timeline towards commercialisation [Source: Analysys Mason, 2017]*



## 4.3 Expected evolution of C-V2X penetration

In the absence of any regulatory intervention, the evolution of C-V2X penetration will primarily depend on the interest that automotive manufacturers have in selecting this technology (rather than IEEE 802.11p) and the likely timeframes for them to implement it in their new vehicles. Automotive OEMs have not yet announced adoption timeframes, but based on primary research conducted for this study we consider it likely that:

- ***C-V2X may enable a wider range of business cases for automotive OEMs, compared to IEEE 802.11p, which is expected to incentivise adoption***. The benefits of using V2N connectivity for communication between vehicles and networks are expected to be a compelling proposition for many automotive OEMs, which may feel that V2V communication on its own does not justify the investment needed for in-car technology. This points to the importance of cellular technology integration and synergies between the two modes of C-V2X communication.

- ***Cellular economies of scale and cost synergies will accelerate C-V2X penetration***. In-vehicle integration costs between cellular (Uu) and V2V (using IEEE 802.11p) could be avoided by adopting C-V2X, and the potential to re-use existing mobile network infrastructure could accelerate V2I penetration and reduce additional infrastructure costs. The collaboration between automotive OEMs and mobile operators, combined with mobile chipset and vendor involvement in the 5GAA, and the fact that a high percentage of new vehicles already have LTE connectivity, is also likely to accelerate wider adoption of a common technology platform among automotive OEMs. The 5GAA's objective of building consensus should enable any barriers to early adoption to be resolved.

- ***In the absence of any regulatory mandate for adoption by a given date, adoption will proceed according to the automotive OEMs' own timescales***. There is already a strong commitment among automotive OEMs to test C-V2X, given their desire for this to be part of a wider progression towards the 5G era, and progression towards full vehicle autonomy.[45] Launch could be phased in across different new vehicle types – either starting from premium vehicles (to maximise the opportunities to offer 'comfort and convenience' services), or by starting from cheaper vehicles (to build penetration and economies of scale rapidly). In the long term, it can be expected that automotive OEMs which choose C-V2X will provide the technology as a standard feature in vehicles: the automotive industry is promoting safety features of new technologies in vehicles very heavily, and C-V2X will complement this commitment, as well as offering the potential to deliver additional telematics/infotainment/entertainment services using the same technology. Once 5G networks are deployed, it is expected that both the V2V/V2I/V2P and V2N capabilities of C-V2X will be further expanded.

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[45] Vehicle autonomy is defined in levels, with current ADAS systems reaching Level 3/Level 4 autonomy. Full autonomy is defined as Level 5.

However, a key risk that various automotive OEMs and mobile industry representatives expressed during this study is the possibility of an EC mandate restricting V2X technology choice in Europe, which might hinder wider C-V2X and 5G adoption.

In this context of uncertainty, various scenarios for the evolution of C-V2X adoption can be envisaged:

- **Scenario 1 (base case)** – adoption and timing of deployment is determined by automotive OEMs, in the absence of any regulatory measures.
- **Scenario 2 (2020 EC mandate on V2V/V2I)** – an EC mandate requiring all new vehicle models to support the EC-defined ‘Day 1’ and ‘Day 1.5’ services from 2020 results in C-ITS services using IEEE 802.11p technology for V2V and V2I.
- **Scenario 3 (2023 EC mandate on V2V/V2I)** – an EC mandate requiring all new vehicle models to support ‘Day 1’ and ‘Day 1.5’ services from 2023 results in C-ITS services using LTE PC5 technology for V2V and V2I.
- **Scenario 4 (equitable 5.9GHz use)** – C-V2X and IEEE 802.11p technologies co-exist in 5.9GHz spectrum, with an equitable division of spectrum enabling adoption of both technologies based on market demand.

These scenarios are explored further in Section 5, where we describe the analysis that we have conducted to quantify the benefits of C-V2X.

# 5 Quantifying the benefits of C-V2X for connected and automated vehicles

In this section we describe modelling conducted as part of this study to quantify the costs and benefits of C-V2X in the EU. Further details of our modelling approach and detailed assumptions are provided in Annex B.

## 5.1 Modelling assumptions and scenarios

### 5.1.1 Definition of scenarios

As highlighted in Section 4.3, in the absence of any regulatory intervention, the evolution of C-V2X penetration would primarily depend on the interest that automotive OEMs have in deploying V2X communications, and C-V2X specifically (rather than IEEE 802.11p), as well as the likely timeframes for implementing C-V2X in their new vehicles.

One of the key risks that various automotive OEMs and the mobile industry expressed during this study is the possibility of an EC mandate restricting the V2X technology choice in Europe. To reflect this uncertainty, we developed four modelling scenarios for the evolution of C-V2X adoption. The scenarios were defined to produce quantitative results that highlight changes in the magnitude of the overall costs and benefits associated with different timescales and volumes of adoption, as well as to distinguish the relative differences in the net benefits, depending on whether PC5 or IEEE 802.11p is adopted in vehicles, and the extent to which synergies with cellular networks are exploited for provision of V2I/P.

***Scenario 1 (Base case)*** *– Adoption and timing of deployment of C-V2X and IEEE 802.11p is determined by OEMs, in the absence of any regulatory measures*

In this scenario, automotive OEMs would likely implement V2X services in different timeframes, depending on the renewal cycles for their vehicle models. Launch would be phased in across different new vehicle types – either starting from premium vehicles (to maximise the opportunities to offer 'comfort and convenience' services), or by starting from cheaper vehicles (to build penetration and economies of scale rapidly) – but adoption would progressively cover a greater number of vehicle models.

We assume that not all automotive OEMs would use the same technology (IEEE 802.11p or PC5) for V2V services initially. Given the limited incentives to deploy 5.9GHz RSUs, beyond EU funding (e.g. the C-Roads Platform[46]), in this scenario we assume that V2I services would be provided in combination with cellular networks (i.e. using MNOs' own spectrum for V2N).

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[46] See https://www.c-roads.eu/platform.html

In this scenario, therefore, we assume that deployment of 5.9GHz RSUs would be limited to locations where IEEE 802.11p and/or PC5-based RSUs were needed, in the absence of cellular infrastructure being available for V2N (e.g. at traffic signals).

For V2N to be achievable, we assume that MNOs would work with road operators so that vehicle sensor and other V2X data could be made available for road management, and to ensure that necessary network connections were available at appropriate places in the road network, while complying with data protection requirements for the exchange of data.

No direct-mode communications interoperability between vehicles using IEEE 802.11p and PC5 for V2V communications would be expected to occur, and hence the only means of conveying messages between vehicles equipped with different V2V technologies would be via cellular networks (i.e. assuming all vehicles had embedded LTE functionality for V2N).

In this scenario, we assume that vehicles without an embedded IEEE 802.11p or PC5 interface would be able to use some V2I and V2P services via the PC5 or Uu connectivity of a smartphone, or a dedicated after-market device with PC5 or Uu connectivity.

***Scenario 2 (2020 EC mandate on V2V/V2I)*** *– An EC mandate requires all new vehicle models to support the EC-defined ‘Day 1’ and ‘Day 1.5’ services from 2020, via IEEE 802.11p technology*

In this scenario, we assume that an EC mandate for Day 1 and Day 1.5 services to be supported in all new vehicles types would drive adoption of IEEE 802.11p for V2V and V2I communications. This scenario assumes that an EC mandate would start in 2020 and would include a ramp-up period of four years for automotive OEMs to start including IEEE 802.11p in all their new vehicles.

We assume that road operators would be required to install new RSUs to support V2I communications and to expand their RSU infrastructure to currently uncovered areas. We assume that RSU roll-out would take place over a period of four years. In practice, we note that this timeframe is optimistic – without an incentive to deploy RSUs, road operators would be expected deploy these over a longer timeframe, in line with replacement cycles for existing roadside infrastructure (which can be quite long). It should be noted that an extended roll-out period for V2I would mean that the full capabilities of V2X were not available.

In this scenario we assume that vehicles without embedded IEEE 802.11p functionality would not be able to use V2V/V2I services, as smartphone vendors are unlikely to include an IEEE 802.11p transceiver in their devices. Vehicles equipped with IEEE 802.11p for V2V/V2I, and with LTE Uu for V2N, could communicate via cellular networks.

***Scenario 3 (2023 EC mandate on V2V/V2I)*** *– An EC mandate requires all new vehicle models to support ‘Day 1’ and ‘Day 1.5’ services via LTE PC5 technology*

In this scenario, we assume that an EC mandate for Day 1 and Day 1.5 services to be supported in all new vehicle types would drive adoption of C-V2X based PC5 for V2V, and V2I, communications. We assume that the EC would allow time for PC5 to mature and would mandate fitment from 2023 onwards. Given this slightly later date of implementation compared to Scenario 2, we assume a shorter ramp-up period of three years for automotive OEMs to include C-V2X PC5 in all new vehicles.

Similar to Scenario 2, we assume that road operators would be required to add to existing roadside infrastructure with PC5-based RSUs. In this scenario we assume a three-year roll-out, during which road operators would expand their RSU infrastructure coverage to support V2I communications. We assume that new PC5-based RSUs would exploit LTE-based economies of scale and hence would be cheaper to deploy than new IEEE 802.11p-based RSUs. We also assume that the number of deployed RSUs would be lower in Scenario 3 than in Scenario 2, since the dual-mode capabilities of C-V2X can be better exploited in this scenario to use existing mobile networks for appropriate locations and/or services (for example, in-vehicle fitment costs would be lower, if PC5 and Uu interfaces were via a single chipset).

In this scenario, we assume that vehicles without an embedded PC5 interface would be able to use some V2I and V2P services via a smartphone, or via Uu connectivity.

***Scenario 4 (Equitable 5.9GHz use)** – C-V2X and IEEE 802.11p technologies co-exist in 5.9GHz spectrum*

Finally, Scenario 4 represents the 5GAA's 'co-existence' scenario, whereby a division of spectrum resources in the 5.9GHz band between PC5-based V2V, and IEEE 802.11p-based V2V, is assumed.[47]

Similar to Scenario 1, we assume that some automotive OEMs would use IEEE 802.11p for V2V/V2I communications and cellular (Uu) for V2N, while others would use PC5 for V2V/V2I, and all vehicles would use cellular for V2N. PC5 adoption would be higher than in Scenario 1, because the agreed co-existence solution would remove the risk that early adoption of IEEE 802.11p by some automotive OEMs could prevent a subsequent adoption of PC5 by others (e.g. due to the risk of congestion in the 5.9GHz band).

No direct-mode communications interoperability would be expected between vehicles using IEEE 802.11p and PC5 for V2V communications, and hence the only means of conveying messages between vehicles that were equipped with different V2V technologies would be via cellular networks (i.e. assuming all vehicles had embedded LTE functionality for V2N).

We assume that vehicles without an embedded V2V interface would be able to use some V2I and V2P services via the PC5 or Uu connectivity of a smartphone, or a dedicated after-market device with PC5 or Uu connectivity.

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[47] The 5GAA's co-existence scenario proposes that each V2V technology would have exclusive access to a 10MHz block in the 5.9GHz band, initially separated by a 10MHz guard band.

### 5.1.2 Key modelling assumptions

*Use cases*

As highlighted in Section 3.1, the number of use cases for C-ITS systems that relate to road safety is potentially significant. While the 'C-ITS Platform' has defined 25 highly beneficial services for priority deployment in the EU, other highly beneficial V2X services are commonly referred to in published literature, including services leading towards fully automated driving.

Based on an extensive literature review, we have defined a list of 17 V2V, V2I and V2P services that we believe would have major socio-economic benefits and would likely be deployed (see Figure 5.1 below). We have grouped these services into three categories:

- **'Information'** services which provide general information to the driver about road traffic, vehicles and conditions, but do not alert the driver to an immediate danger
- **'Warning'** services which provide information to the driver about a potential immediate danger (e.g. collisions)
- **'Actuation'** services, including services leading towards fully automated cars (e.g. active braking).

A detailed definition of the scope of each of these services is provided in Figure 5.1 below.

*Figure 5.1: V2X services included in our modelling [Source: Analysys Mason, 2017]*

| Service | Type | Category |
|---|---|---|
| Do not pass warning | V2V | Warning |
| Traffic jam ahead warning (e.g. roadworks, accident, etc.) | V2V | Warning |
| Slow or stationary vehicle(s) warning | V2V | Warning |
| Cooperative collision warning (e.g. cars, motorbikes, emergency vehicles) | V2V | Warning |
| Emergency brake light | V2V | Warning |
| Hazardous location notification | V2V | Warning |
| Vulnerable road user protection | V2P | Warning |
| In-vehicle speed limits | V2I or V2N | Information |
| In-vehicle signage | V2I or V2N | Information |
| Probe vehicle data | V2I or V2N | Information |
| Shockwave damping | V2I or V2N | Information |
| Traffic signal priority requested by designated vehicles | V2I or V2N | Information |
| Green light optimal speed advisory (GLOSA) | V2I or V2N | Information |
| Traffic information for smarter junction management (incl. signal violation, traffic management) | V2I or V2N | Information |
| CACC | V2V | Actuation |
| Active braking | V2V | Actuation |

We have excluded from this list a number of services shortlisted by the C-ITS Platform (e.g. traffic information and smart routeing, loading zone management, zone access control management, on-street / off-street parking information and management, park-and-ride information, information on alternative fuelled vehicle charging and fuelling stations), as we believe these services largely exist and hence would not generate additional socio-economic benefits over the period considered. The weather conditions service has also been eliminated, in line with the C-ITS Phase 2 report.

*Vehicle bundle segments*

We have defined three segments of vehicles, based on their ability to access some/all the V2X services listed in Figure 5.1 by scenario:

- ***Vehicles with warning services only***. This segment is relevant to Scenarios 2 and 3, as road operators would need to expand roadside infrastructure to enable V2I communications (unless existing cellular infrastructure was used, for V2N). As we assume this deployment would happen over a three- or four-year period, we expect that vehicles with IEEE 802.11p / LTE PC5 and located in areas with no RSU coverage (or where V2X-enabled RSUs are not added) would be unable to access V2N-based information services. Hence these vehicles would rely on standard V2V/V2P-based warning services only.

- ***Vehicles with warning and information services***: This segment applies to all scenarios and includes all vehicles with a IEEE 802.11p / PC5 interface that provides access to V2V-based warning services and V2I-based information services. It also includes those vehicles without a IEEE 802.11p or LTE PC5 interface, which would access some V2I and V2P services via the Uu connectivity or PC5 interface of a smartphone, or a dedicated after-market device. It does not include vehicles with access to CACC and active-braking services.

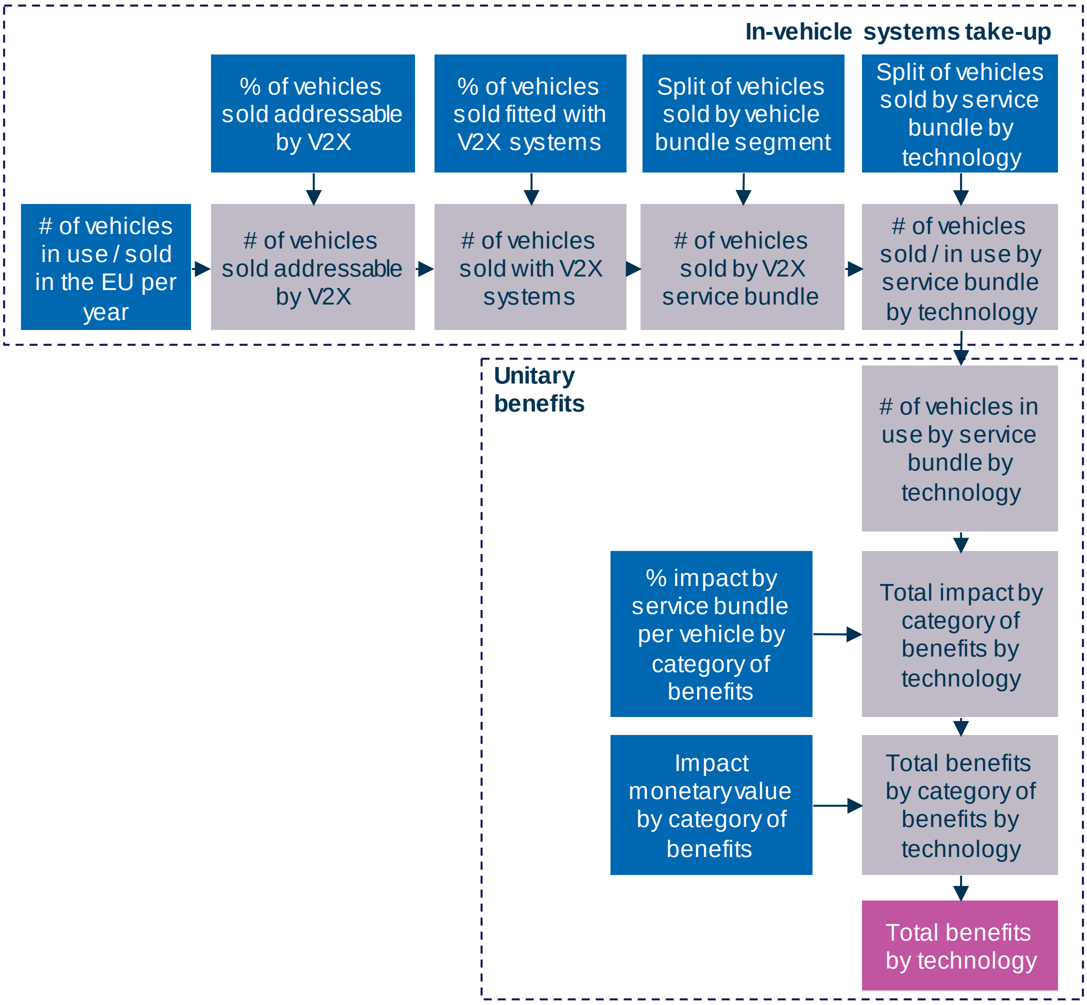
- ***Vehicles with warning, information and actuation services***. Vehicles in this segment can access all 17 key V2X services listed above. It is relevant to all scenarios and includes all vehicles with a IEEE 802.11p / PC5 interface that provides access to V2V-based warning, V2I-based information and actuation services (e.g. CACC, active braking). We assume that actuation services would not be available at V2X launch date under any scenario, but that certain new vehicle models would be progressively equipped in the later years of the forecast.

*Benefits*

Our modelling of the benefits of C-ITS systems quantifies the combined cost savings from reductions in road accidents, in fuel consumption, in $CO_2$ emissions and in time spent on the road (‘traffic efficiency’).

At a high level, our approach to quantifying these benefits is based on an estimate of the number of vehicles using V2X services by vehicle bundle segment and technology, and an estimate of the unitary benefit per vehicle by service bundle and technology (as summarised in Figure 5.2).

*Figure 5.2: Overview of methodology for modelling benefits [Source: Analysys Mason, 2017]*



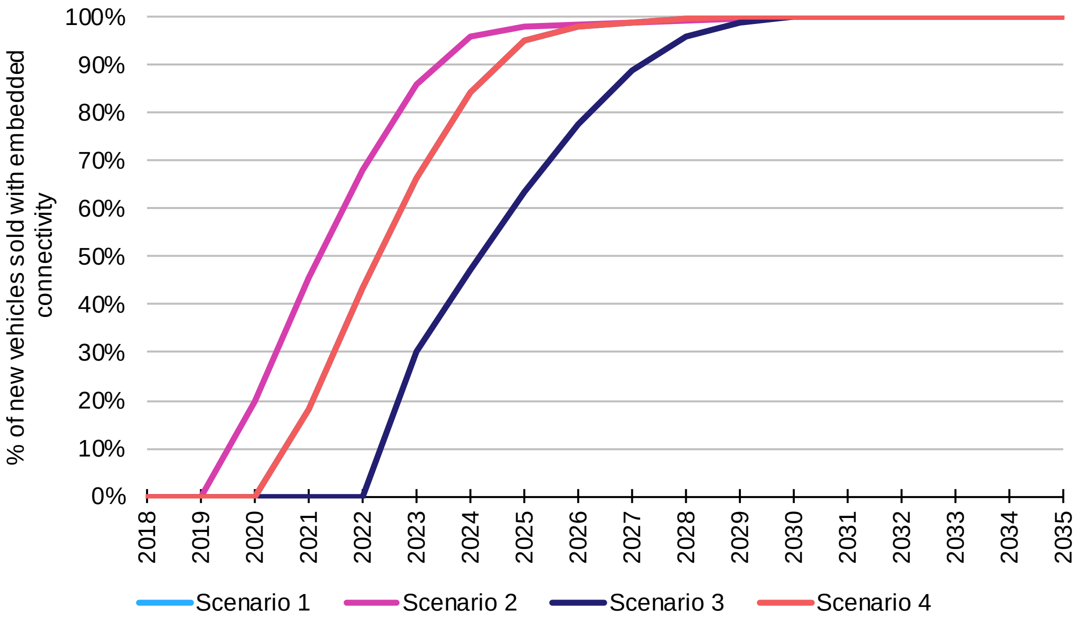
The rest of this section provides an overview of the key assumptions used in the model on the take-up of in-vehicle systems and on the unitary benefits per vehicle.

► *In-vehicle systems take-up*

To estimate the total benefits of V2X services, we have used published data and projections of the number of new vehicles sold per year and assumptions about how the penetration of V2X services will evolve over time.

We assume that only new vehicles sold with embedded Uu connectivity could be potentially equipped with IEEE 802.11p or LTE PC5. However, the fitment of a V2X chipset would depend on OEMs’ product renewal lifecycle, i.e. only new vehicle models or vehicles in the middle of their lifecycle would be addressable by IEEE 802.11p or LTE PC5. Figure 5.3 provides an overview of our assumptions regarding the evolution of the proportion of vehicles sold with embedded connectivity which would be addressable by V2X (i.e. by IEEE 802.11p or LTE PC5) under each scenario.

*Figure 5.3: Evolution of the proportion of new vehicles sold with embedded connectivity addressable by V2X, by scenario*[48] *[Source: Analysys Mason, 2017]*



In Scenarios 1 and 4, we assume that automotive OEMs would phase in the adoption of V2X across different new vehicle types – e.g. starting from premium vehicles (to maximise opportunities for ‘comfort and convenience’ services to be offered). However, the potential for automotive OEMs to implement C-V2X very quickly is strong, given the involvement of automotive OEMs in the 5GAA, the 5GAA’s objective of building consensus and a general acknowledgment of the overall benefits of C-V2X adoption in vehicles, leading towards greater connectivity with 5G in due course.

In Scenarios 2 and 3, we assume that OEMs would be required to include IEEE 802.11p or LTE PC5 in all their new vehicles, within a ramp-up period for the two technologies of four and three years respectively. Figure 5.4 below shows our assumptions regarding the evolution of the proportion of addressable vehicles equipped with a V2X chipset (IEEE 802.11p or LTE PC5) under each scenario.

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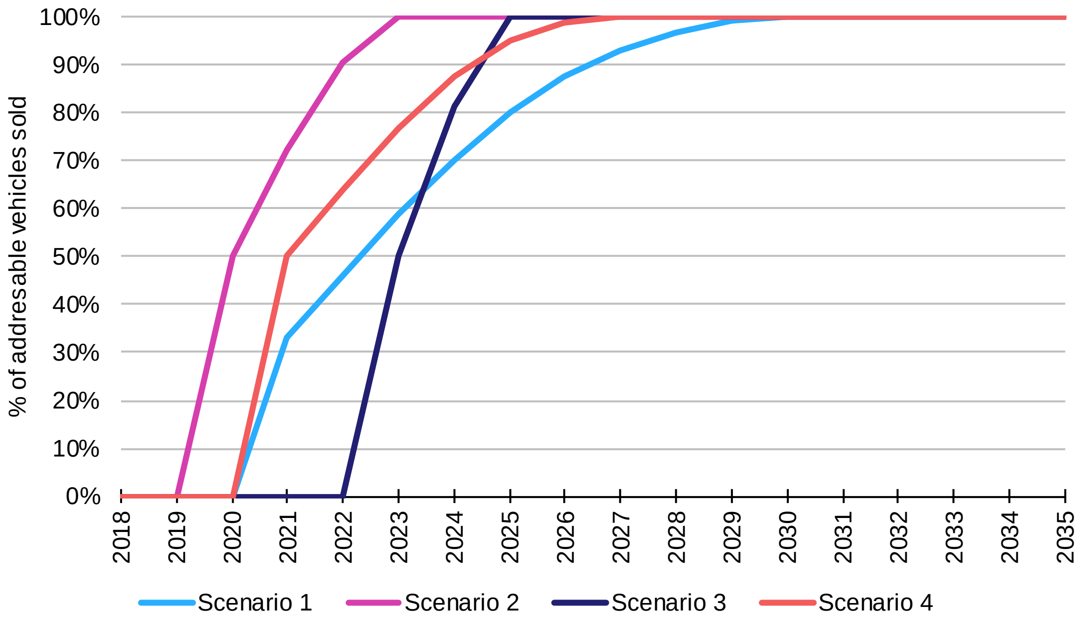
[48] The assumption curves for Scenarios 1 and 4 are overlapping, since both scenarios follow the same timeline.

*Figure 5.4: Evolution of the proportion of addressable vehicles sold equipped with V2X, by scenario [Source: Analysys Mason, 2017]*



As discussed earlier (see page 40), we have defined three segments of vehicles using V2X services, based on their access to various bundles of services: V2V/V2P-based warning services only; both warning and information services; and warning, information and actuation services. The following points should be noted regarding the split of vehicles into these three segments:

- Across all scenarios, we assume that all new vehicles sold with a V2V interface (IEEE 802.11p or LTE PC5) would be able to at least use warning services.
- In Scenarios 1 and 4, we assume that all vehicles sold would be able to access V2N services from day 1 via MNOs' existing cellular networks, and with the evolution of mobile networks to 5G (leveraging cellular technology migration and economies of scale), the potential for fully automated driving (referred to as actuation services in our model) would increase. V2I via 5.9GHz RSUs is assumed at traffic intersections (e.g. traffic signals).
- In Scenarios 2 and 3, we assume that V2I would be provided by 5.9GHz RSUs, requiring a large-scale investment and upgrade to existing RSUs. Vehicles located in areas with no RSU coverage or where V2X-enabled RSUs have not been added would be unable to access V2I-based information services from RSUs, and would rely on their standard V2V/V2P-based warning services only, until the coverage of V2X-enabled RSU infrastructure expanded. In Scenario 2, we assume that no vehicle would use actuation services, as these are not on the EC's list of Day 1 and Day 1.5 services.

Figure 5.5 below provides an overview of our assumptions regarding the split of vehicles sold using V2X by service bundle segment in 2025 and 2035, under all four scenarios.

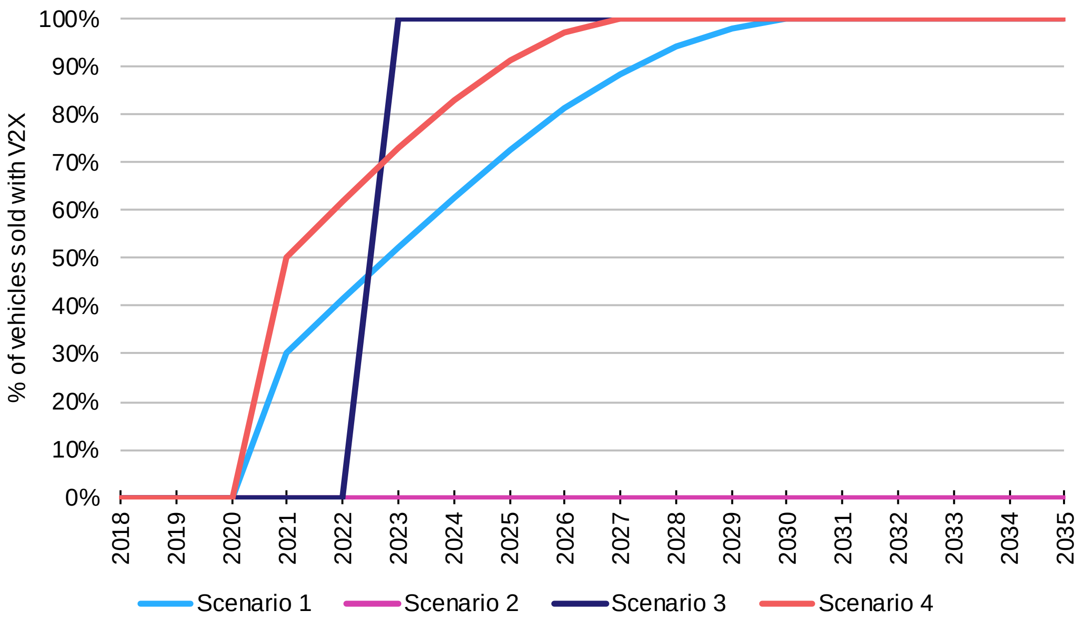
*Figure 5.5: Overview of the split of new vehicles sold with V2X services by service bundle segment and by scenario [Source: Analysys Mason, 2017]*

| Vehicle service bundle segment | Scenario 1 | | Scenario 2 | | Scenario 3 | | Scenario 4 | |
|---|---|---|---|---|---|---|---|---|
| | 2025 | 2035 | 2025 | 2035 | 2025 | 2035 | 2025 | 2035 |
| Warning | 0% | 0% | 75% | 25% | 85% | 13% | 0% | 0% |
| Warning + information | 81% | 35% | 25% | 75% | 14% | 77% | 79% | 30% |
| Warning + information + actuation | 19% | 65% | 0% | 0% | 1% | 10% | 21% | 70% |

As discussed in Section 5.1.1, we have used different technology adoption assumptions, depending on the scenario.

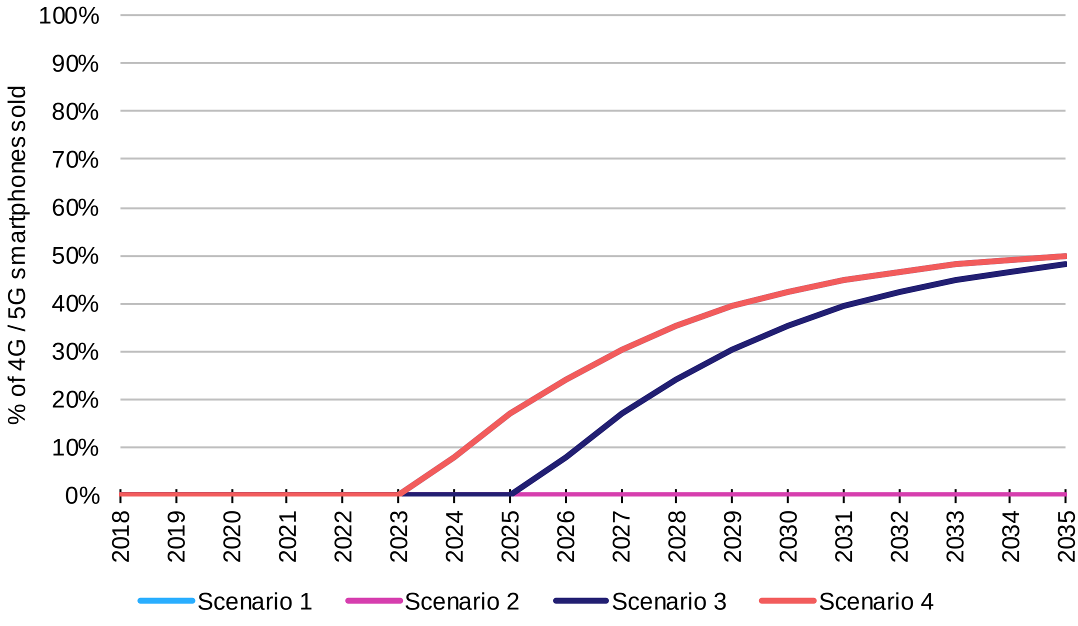
- In the base case, we assume a larger initial market share for IEEE 802.11p, boosted by the early commitment of a few automotive OEMs to include IEEE 802.11p in some of their new vehicle models. In the long run, we assume that automotive OEMs would switch to C-V2X as the technology matured and as 5G was introduced in the market.
- In the equitable 5.9GHz use scenario, we assume a larger initial share for C-V2X, as the agreed co-existence solution would remove the risk that early adoption of IEEE 802.11p by some automotive OEMs could prevent a subsequent adoption of PC5 by others.
- In Scenarios 2 and 3, involving earlier or later EC mandates for V2V/V2I, automotive OEMs would be restricted to using a single technology (respectively IEEE 802.11p and C-V2X) for all V2X connections. Figure 5.6 below provides an overview of the evolution of the share of PC5-based vehicles by scenario.

*Figure 5.6: Evolution of the share of vehicles sold with C-V2X, by scenario [Source: Analysys Mason, 2017]*



As highlighted earlier in this section, in Scenarios 1, 3 and 4 we assume that vehicles without a V2X interface for direct communications could potentially use some "Information" services via a 4G/5G smartphone equipped with PC5 or Uu connectivity. In each scenario, we assume that the first smartphones with a PC5 chipset would be released three years after the launch of C-V2X services for new vehicles with embedded connectivity. In Scenario 2, based on expert feedback provided for this study, we assume that smartphone manufacturers would be unlikely to include an IEEE 802.11p chipset in their smartphones and so no vehicles without a V2X interface could access V2X services. Figure 5.7 below provides an overview of our assumed evolution of the proportion of 4G/5G smartphones equipped with a PC5 chipset.

*Figure 5.7: Evolution of the proportion of 4G/5G phones sold with a PC5 chipset, by scenario*[49] *[Source: Analysys Mason, 2017]*



► *Unitary benefits*

To estimate the total benefits of V2X services, we have used assumptions about the unitary (i.e. per-vehicle) benefits of each individual C-ITS service, and aggregated these for all three segments of vehicles using V2X services (those using V2V/V2P-based warning services only, those with both warning and information services, and those with warning, information and actuation services).

We have assumed a unitary benefit for each individual V2X service by category of impact (safety, fuel consumption, $CO_2$ emissions, traffic efficiency), by type of road (urban, rural, motorway), by vehicle type (passenger cars, commercial vehicles) and by type of connectivity (embedded, after-market).

As an illustration, Figure 5.8 below summarises our assumptions on the mapping of benefits for each V2X service by type of road and category of impact for passenger cars with embedded connectivity.

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[49] Assumption curves for Scenarios 1 and 4 overlap, as both scenarios follow the same timeline.

*Figure 5.8: Overview of maximum unitary impact[50] assumptions by V2X service [Source: Analysys Mason, 2017]*

| | Category of impact | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Safety | | | Fuel consumption / $CO_2$ emissions | | | Traffic efficiency | | |
| V2X service | Urban | Rural | Motorway | Urban | Rural | Motorway | Urban | Rural | Motorway |
| Do not pass warning | – | +3% | – | – | – | – | – | +1% | – |
| Traffic jam ahead warning (e.g. roadworks, accident, etc.) | +3% | +5% | +6% | – | – | – | +2% | +2% | +2% |
| Slow or stationary vehicle(s) warning | +1% | +1% | +1% | – | – | – | – | – | – |
| Cooperative collision warning (e.g. cars, motorbikes, emergency vehicles) | +7% | +3% | +3% | – | – | – | +2% | +2% | +2% |
| Emergency brake light | +3% | +3% | +3% | – | – | – | +1% | +1% | +1% |
| Hazardous location notification | +4% | +7% | +7% | – | – | – | +2% | +2% | +2% |
| Vulnerable road user protection | – | – | – | – | – | – | – | – | – |
| In-vehicle speed limits | +4% | +4% | +4% | – | – | – | –1% | –1% | –1% |
| In-vehicle signage | +1% | +1% | +1% | – | – | – | – | – | – |
| Probe vehicle data | +2% | +4% | +5% | – | – | – | – | – | – |
| Shockwave damping | – | – | +5% | – | – | – | – | – | – |
| Traffic signal priority requested by designated vehicles[51] | – | – | – | – | – | – | – | – | – |
| Green light optimal speed advisory (GLOSA) | – | – | – | +1% | – | – | – | – | – |
| Traffic information for smarter junction management (incl. signal violation, traffic management) | +7% | +7% | - | - | - | - | +5% | +5% | - |
| CACC | - | - | +2% | - | - | +3% | - | - | +3% |
| Active braking | +3% | +3% | +3% | - | - | - | - | - | - |

We have calculated the impact for each service bundle (warning, warning + information, warning + information + actuation) as the sum of the individual impacts of V2X services included in each

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[50] In the table, "+1%" denotes an assumed positive unitary impact from using the V2X service against a given category of impact, "–1%" denotes a negative impact and "–" denotes no impact.

[51] The "Traffic signal priority requested by designated vehicles" V2X service is, by definition, only applicable to certain commercial vehicles (e.g. buses). We have assumed a reduction in fuel consumption of 8.3% and an improvement in traffic efficiency of 9.2% in urban and rural areas.

service bundle. Figure 5.9 below summarises the aggregated unitary benefit by V2X service bundle, by type of road and category of impact for passenger cars with embedded connectivity.

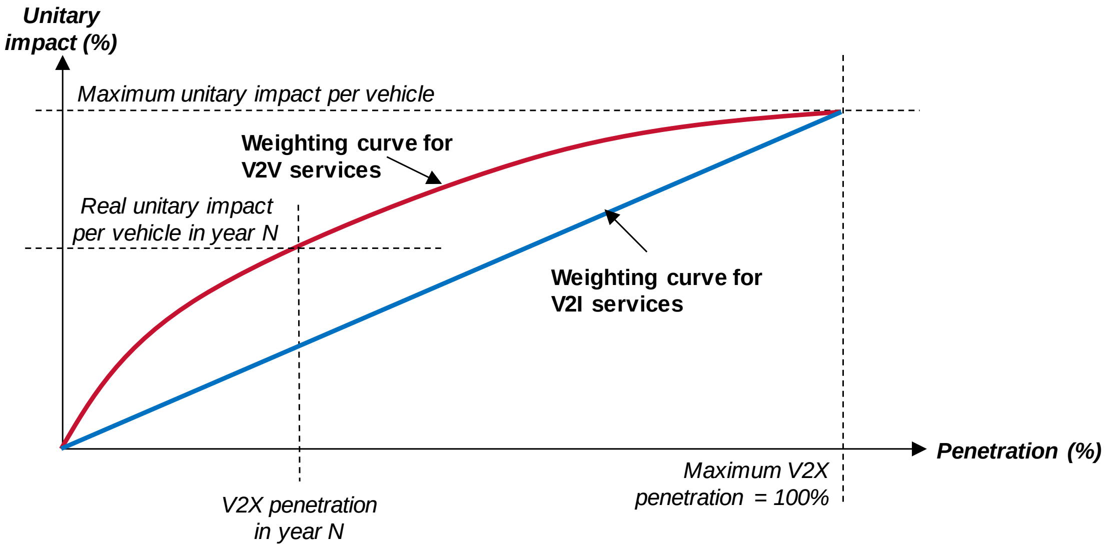
*Figure 5.9: Aggregated unitary benefit by V2X service bundle [Source: Analysys Mason, 2017]*

| V2X service bundle | Category of impact | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Safety | | | Fuel consumption / $CO_2$ emissions | | | Traffic efficiency | | |
| | Urban | Rural | Motorway | Urban | Rural | Motorway | Urban | Rural | Motorway |
| Information | 14% | 16% | 14% | 1% | 4% | 2% | 4% | 4% | -1% |
| Warning | 17% | 23% | 18% | 0% | 0% | 0% | 2% | 2% | 2% |
| Warning + information | 31% | 39% | 33% | 1% | 4% | 2% | 6% | 6% | 1% |
| Warning + information + actuation | 33% | 42% | 36% | 1% | 4% | 5% | 6% | 6% | 4% |

A number of points should be noted:

- We assume similar unitary benefits for C-V2X and IEEE 802.11p. While the range of action of C-V2X is expected to be larger than for IEEE 802.11p we have not tried to estimate the difference in impact between the two technologies, as this was outside the scope of the study.
- The unitary assumptions shown in Figure 5.9 have been set for a theoretical 100% penetration of vehicles by C-V2X or IEEE 802.11p (maximum impact). In reality, the unitary impact per vehicle in a given year will be dependent on the actual penetration of vehicles equipped with V2X services. To reflect this 'network effect', we have applied a weighting curve to scale the unitary benefit as penetration increases. Our research and conversations with 5GAA members suggest that significant benefits could be achieved in some areas (e.g. traffic efficiency, $CO_2$ emissions) even when the penetration is relatively low. As such, we have applied a weighting curve that reflects this assumption (see Figure 5.10 below).

*Figure 5.10: Overview of weighting curve (illustration) [Source: Analysys Mason, 2017]*

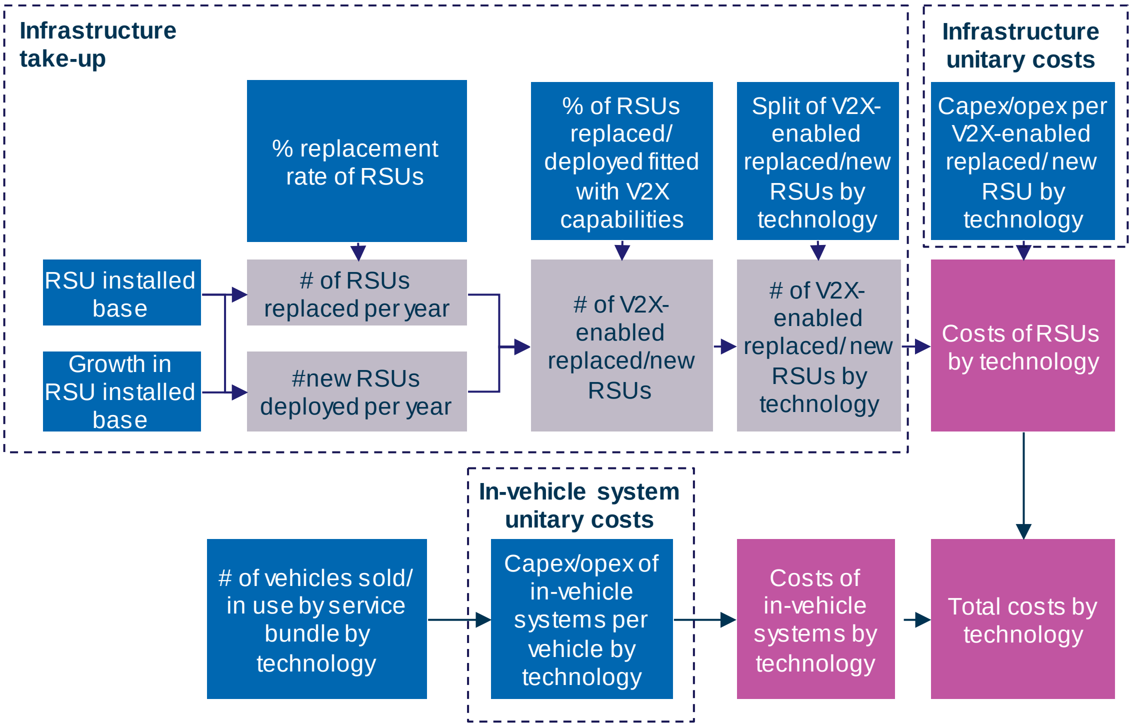


*Costs*

Our cost modelling approach (summarised in Figure 5.11 below) combines a quantification of the costs (capex and opex) of the RSU infrastructure required to support V2I services and the costs of in-vehicle C-ITS systems. Our modelling of the cost of infrastructure applies to all scenarios. In Scenarios 2 and 3, we assume that V2I is provided by 5.9GHz RSUs, requiring a large-scale investment and upgrade to existing RSUs. In Scenarios 1 and 4, V2I via 5.9GHz RSUs is assumed at traffic intersections (e.g. traffic signals).

At a high level, our approach for quantifying the cost of infrastructure is based on an estimate of the number of IEEE 802.11p / PC5-based RSUs deployed and the unitary cost per RSU. Similarly, we have quantified the cost of in-vehicle systems based on an estimate of the number of vehicles sold with/using V2X services and the cost of in-vehicle systems per vehicle.

*Figure 5.11: Overview of cost modelling methodology [Source: Analysys Mason, 2017]*



The rest of this section provides an overview of key assumptions used in the model relating to in-vehicle system unitary costs, infrastructure take-up and infrastructure unitary costs.

► *Infrastructure take-up*

In Scenarios 2 and 3, we assume that, over a period of a few years, road operators would be required to augment existing infrastructure with V2X-enabled (802.11p or PC5-based) RSUs to support V2I communications and to expand their RSU infrastructure coverage. In Scenarios 1 and 4, we assume that RSUs located at traffic intersections would be complemented by a V2X-enabled RSU.

***V2X-enabled new RSUs*** are V2X-enabled RSUs rolled out by road operators to extend their existing RSU coverage. We assume that road operators would be required to increase their RSU density significantly in urban and rural areas under scenarios where V2I services over RSUs (rather than over mobile networks) were mandated. On motorways, we assume a moderate growth in RSUs, as it is expected that motorways already have extensive coverage from roadside infrastructure. Figure 5.12 below provides an overview of our key assumptions on current roadside infrastructure, and expected growth between 2016 and 2035.

*Figure 5.12: Overview of roadside infrastructure density by road type, and growth by scenario [Source: Analysys Mason, 2017]*

| Scenario | Road type | Roadside infrastructure density, 2016 | Growth, 2016–2035 |
|---|---|---|---|
| Scenario 1 | Urban road | 1 per 5km | +7.5% |
| | Rural road | 1 per 10km | +7.5% |
| | Motorway | 1.50 per km | +5.0% |
| Scenario 2 | Urban road | 1 per 5km | +20.0% |
| | Rural road | 1 per 10km | +7.5% |
| | Motorway | 1.50 per km | +5.0% |
| Scenario 3 | Urban road | 1 per 5km | +20.0% |
| | Rural road | 1 per 10km | +10.0% |
| | Motorway | 1.50 per km | +5.0% |
| Scenario 4 | Urban road | 1 per 5km | +7.5% |
| | Rural road | 1 per 10km | +7.5% |
| | Motorway | 1.50 per km | +5.0% |

***V2X-enabled RSUs*** are rolled out by road operators to add functionality to existing roadside infrastructure. In Scenario 2, we assume that existing roadside infrastructure would be added to over a four-year period (2020 to 2023) and in Scenario 3 over a three-year period (2023 to 2025). Outside this period, we assume an average annual roadside infrastructure replacement rate of 5.0%. In both scenarios, we assume that existing roadside infrastructure would be upgraded to IEEE 802.11p / PC5-based RSUs. In Scenarios 1 and 4, in the absence of an EC mandate, we assume that new RSUs would be added at an average rate of 5.0% over the modelling period.

► *Infrastructure unitary costs*

Figure 5.13 below summarises our key cost (capex and opex) assumptions by cost element for roadside infrastructure. The following points should be noted:

- We assume similar capex costs for new and replaced roadside infrastructure, as both would require loop replacement. We assume that V2X-enabled RSUs would not require traffic management or loop cutting and would therefore incur lower hardware installation costs than traditional RSUs. However, V2X-enabled RSUs are expected to include additional components (radio frequency module, microcontrollers, security layers, etc.), which would translate into higher equipment costs. We assume similar capex costs for IEEE 802.11p and PC5-based RSUs, as the difference in chipset costs is likely to be negligible compared to the overall cost of the RSU.

- We assume that V2X-enabled RSUs would generate higher opex costs than traditional RSUs, due to the additional maintenance associated with more-complex hardware. We assume similar opex costs for both IEEE 802.11p and PC5-based RSUs.

*Figure 5.13: Overview of infrastructure costs by technology [Source: Analysys Mason, 2017]*

| Cost type | Cost element | Base value[52] (2016) | | | | | | Annual growth (2018–2035) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | New RSU (EUR) | | | Replaced RSU (EUR) | | | | | |
| | | Traditional | PC5 | 802.11p | Traditional | PC5 | 802.11p | Traditional | PC5 | 802.11p |
| **Capex (one-off cost)** | Equipment | 1200 | 3500 | 3500 | 1200 | 3500 | 3500 | –2% | –2% | –2% |
| | Hardware installation | 1500 | 1000 | 1000 | 1500 | 1500 | 1500 | +2% | +2% | +2% |
| | **TOTAL CAPEX** | **2700** | **4500** | **4500** | **2700** | **5000** | **5000** | | | |
| **Opex (annual cost)** | Backhaul | 200 | 200 | 200 | 200 | 200 | 200 | –2% | –2% | –2% |
| | Security | 40 | 40 | 40 | 40 | 40 | 40 | –2% | –2% | –2% |
| | Power consumption | 20 | 20 | 20 | 20 | 20 | 20 | –2% | –2% | –2% |
| | Maintenance | 150 | 225 | 225 | 150 | 225 | 225 | +2% | +2% | +2% |
| | **TOTAL OPEX** | **210** | **285** | **285** | **210** | **285** | **285** | | | |

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[52] For simplicity, this table provides the weighted average cost per RSU across all types of road.

- *In-vehicle system unitary costs*

In capex terms, we assume that C-ITS systems would be cheaper to implement for LTE PC5 than for IEEE 802.11p (see Figure 5.14). This is partly because an integrated PC5/Uu chipset solution is expected, but also because higher penetration is envisaged, with greater economies of scale as penetration increases. Integrated chipsets are not expected for IEEE 802.11p technology and cellular, and so these solutions will continue to require dual chipsets and antenna systems to be installed in vehicles. We assume similar opex costs for both C-V2X and IEEE 802.11p.

*Figure 5.14: Overview of in-vehicle C-ITS system costs by technology [Source: Analysys Mason, 2017]*

| Cost type | Cost element | Base value (2016) | | Annual growth (2017–2035) | |
|---|---|---|---|---|---|
| | | PC5 | IEEE 802.11p | PC5 | IEEE 802.11p |
| **Capex (one-off cost)** | Antenna | 5 | 10 | –2% | –1%<br>(–2% in Scenario 2) |
| | Systems integration | 20 | 20 | +2% | +2% |
| | Transceiver and chipset | 20 | 40 | –2% | –1%<br>(–2% in Scenario 2) |
| | Electronic control unit (ECU) | 30 | 30 | –2% | –1%<br>(–2% in Scenario 2) |
| | **TOTAL CAPEX** | **75** | **100** | | |
| **Opex (annual cost)** | Backhaul | 3 | 3 | –2% | –1%<br>(–2% in Scenario 2) |
| | Security | 2 | 2 | –2% | –1%<br>(–2% in Scenario 2) |
| | Application | 3 | 3 | –2% | –1%<br>(–2% in Scenario 2) |
| | Maintenance | 7 | 7 | +2% | –1%<br>(–2% in Scenario 2) |
| | Licensing | N/A | N/A | | |
| | **TOTAL OPEX** | **15** | **15** | | |

## 5.2 Summary of results

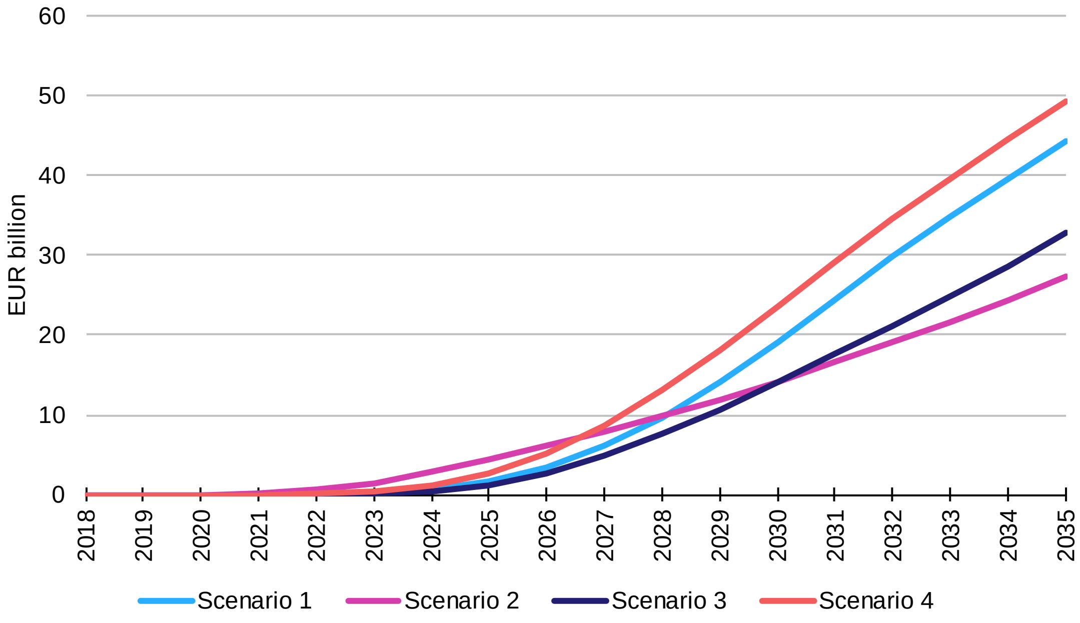
### 5.2.1 Overview

*Benefits*

Overall benefits vary considerably by scenario, as shown in Figure 5.15. Benefits are the highest in in the equitable 5.9GHz use scenario (Scenario 4), which involves a greater proportion of vehicles using ‘actuation’ services and a more rapid increase in overall V2X penetration than any other scenario, reflecting the greater certainty regarding PC5 deployment in 5.9GHz. Another key benefit of this scenario is that the more widespread use of Uu connectivity to provide V2N services avoids the additional costs of upgrading and replacing RSUs with 5.9GHz connectivity for V2I.

In the 2023 EC mandate for V2V/V2I scenario (Scenario 3), we assume widespread use of PC5 technology for V2V/V2I, supported by PC5-based RSUs, without leveraging existing cellular networks for V2N. In Scenario 3, the benefits are lower than in either the base case or the equitable 5.9GHz use scenario. This is due to additional roll-out costs for the roadside infrastructure and because the time needed for road operators to deploy roadside infrastructure would delay the delivery of V2I services. We also expect that fewer vehicles would use ‘actuation’ services, as we assume these would be unlikely to form part of any EC mandate for V2V/V2I services (the basis for this scenario). The 2020 EC mandate for V2V/V2I scenario generates lower benefits than Scenario 3, reflecting the assumption that vehicles which only support an IEEE 802.11p interface (i.e. without either PC5 or Uu connectivity) would not be able to use V2P or V2N services (and so could not create the additional benefits that V2P and V2N produce in other scenarios).

*Figure 5.15: Evolution of the benefits, by scenario [Source: Analysys Mason, 2017]*



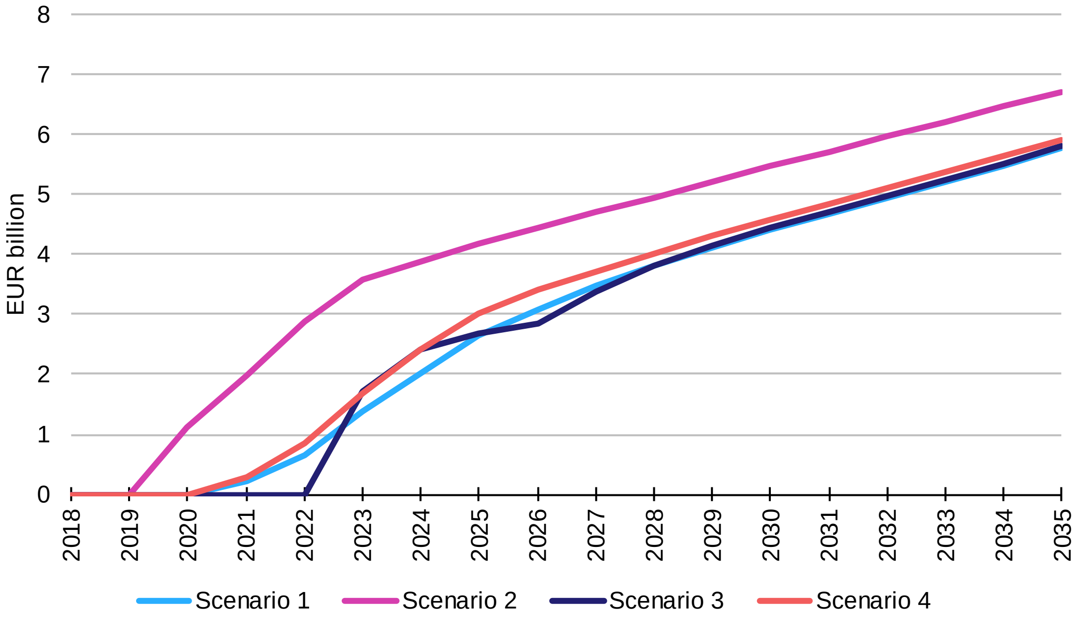
*Costs*

By contrast, infrastructure costs are highest for Scenario 2 (see Figure 5.16), due to the high costs for road operators to upgrade and expand RSU deployment for IEEE 802.11p-based V2I services. In Scenarios 1 and 4, there is assumed to be greater reliance on existing cellular coverage for V2N, thus avoiding the need for large-scale 5.9GHz RSU roll-out.

For automotive OEMs, overall costs would be lower in Scenario 3 than in Scenario 2, as in-vehicle systems would be cheaper to implement for C-V2X than for IEEE 802.11p (due to stronger PC5/Uu chipset integration and greater economies of scale). For Scenarios 1 and 4, where vehicles would need to be equipped with V2V and Uu communications capability, costs would be lower for vehicles using PC5 with Uu, rather than IEEE 802.11p with Uu, resulting from lower in-vehicle integration costs for the former scenario.

In Scenarios 1 and 4, we assume that the deployment of 5.9GHz RSUs would be limited to locations where IEEE 802.11p and/or PC5-based RSUs were needed, in the absence of cellular infrastructure being available for V2N (e.g. at traffic signals). In other locations, we assume that MNOs would perform the necessary upgrades to support the Uu Release 14 features as part of standard network and performance upgrades.

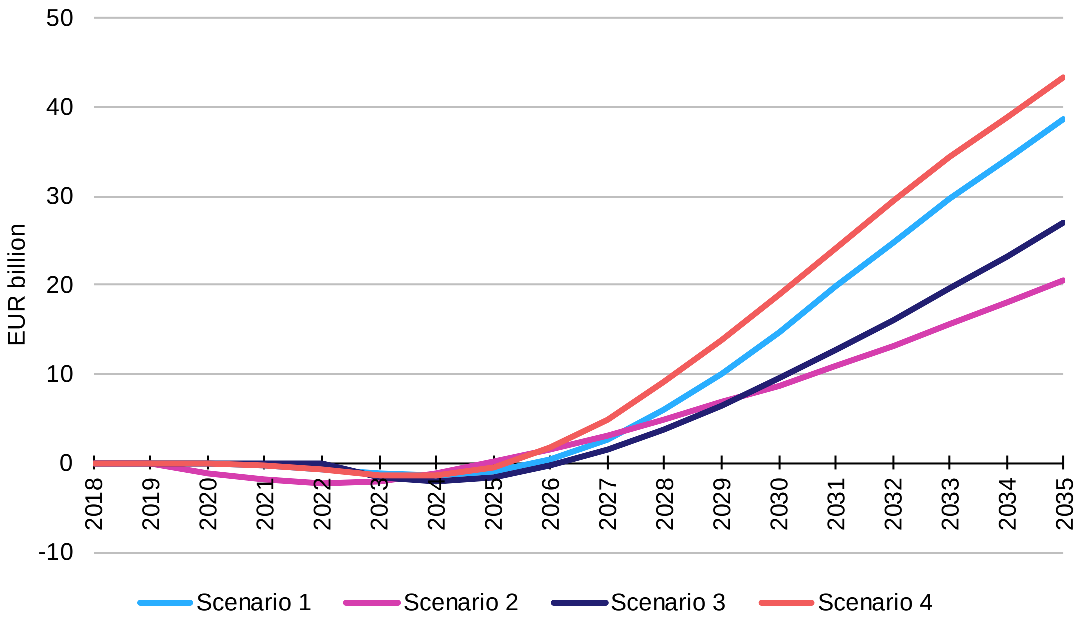
*Figure 5.16: Evolution of the costs, by scenario [Source: Analysys Mason, 2017]*



*Net benefits*

Figure 5.17 shows that the highest net benefits – EUR43 billion – would come from Scenario 4, followed closely by Scenario 1 (EUR39 billion). Scenario 3 would generate around EUR27 billion of monetised benefits, as a result of lower benefits and slightly higher costs, while the high costs and relatively lower benefits of Scenario 2 suggest that it would generate lower net benefits than all other scenarios (EUR20 billion).

*Figure 5.17: Evolution of net benefits, by scenario [Source: Analysys Mason, 2017]*



### 5.2.2 Results by scenario

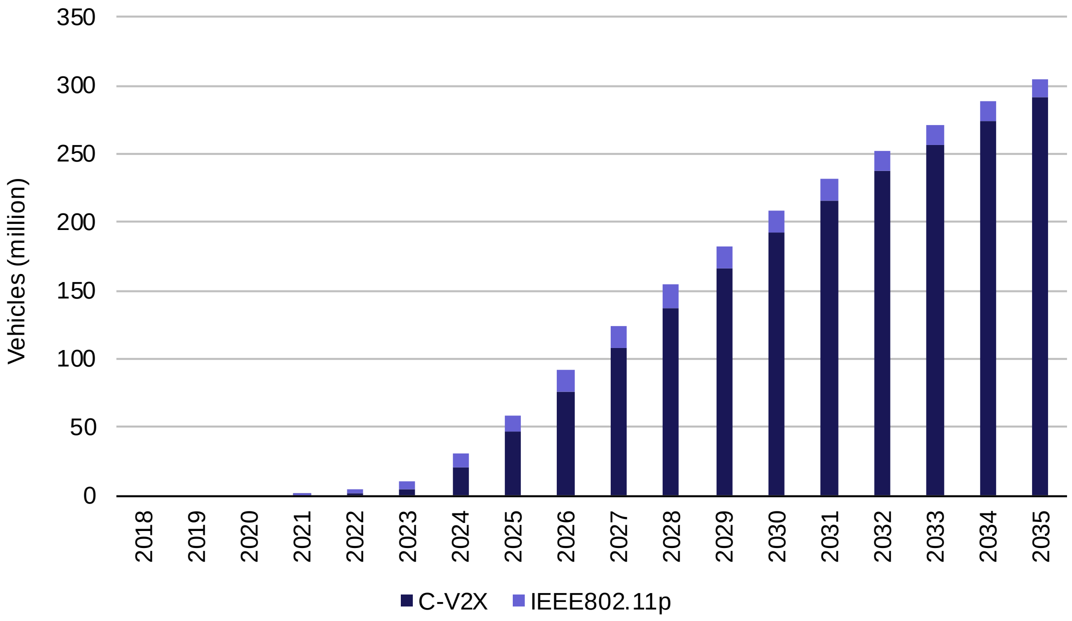
This subsection provides an overview of the key results by scenario. In particular, we discuss how the number of vehicles using V2X services (and the implied benefits and costs) are split between C-V2X and IEEE 802.11p technologies.

*Scenario 1 – base case*

Overall, the number of vehicles equipped with embedded V2X services is expected to increase at a relatively moderate rate initially in Scenario 1, as automotive OEMs would equip only a portion of their new vehicle models (see Figure 5.18 below). Over time, however, we would expect V2X to be fitted in a greater number of vehicle models, while vehicles that did not have embedded V2X services would use PC5-based smartphones to access some V2I and V2P services.

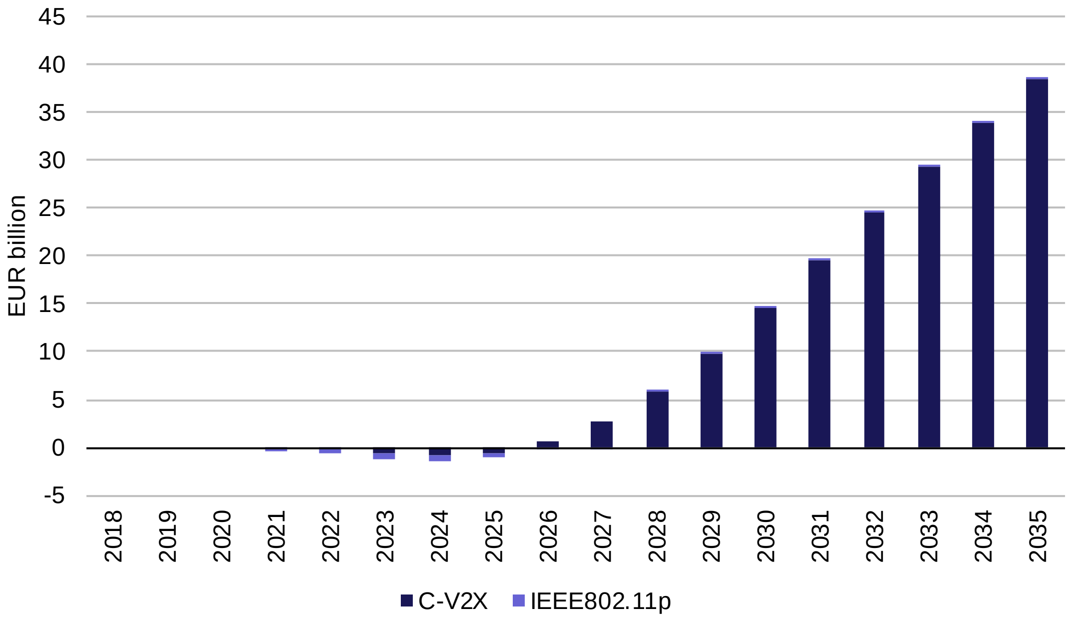
In this scenario, some automotive OEMs would equip some new vehicle models with IEEE 802.11p in the first few years after launch of V2X, while others would wait until LTE PC5 was available and would deploy PC5 for V2V communications along with cellular for V2I/V2N. There would be no interoperability between the two technologies. A key risk in this scenario, where different automotive OEMs would deploy different V2V communication solutions, is that inefficient use of the 5.9GHz band could occur, because the two technologies are not compatible. One way to mitigate this risk could be to put ‘equitable access’ principles in place in the band between the two technologies – such as the 5GAA’s co-existence proposal, as described for Scenario 4.

*Figure 5.18: Evolution of the number of vehicles using V2X services in Scenario 1, by technology [Source: Analysys Mason, 2017]*



Net benefits are expected to reach over EUR39 billion in 2035 (see Figure 5.19 below). The C-V2X share of net benefits is expected to be larger than its share of the number of vehicles using V2X services, as the unitary impact per vehicle equipped with C-V2X is expected to be larger than for IEEE 802.11p. This is driven by the (non-linear) increase in the unitary impact per vehicle with the overall penetration of V2X ('network effect') and by the assumed non-interoperability of C-V2X and IEEE 802.11p technologies.

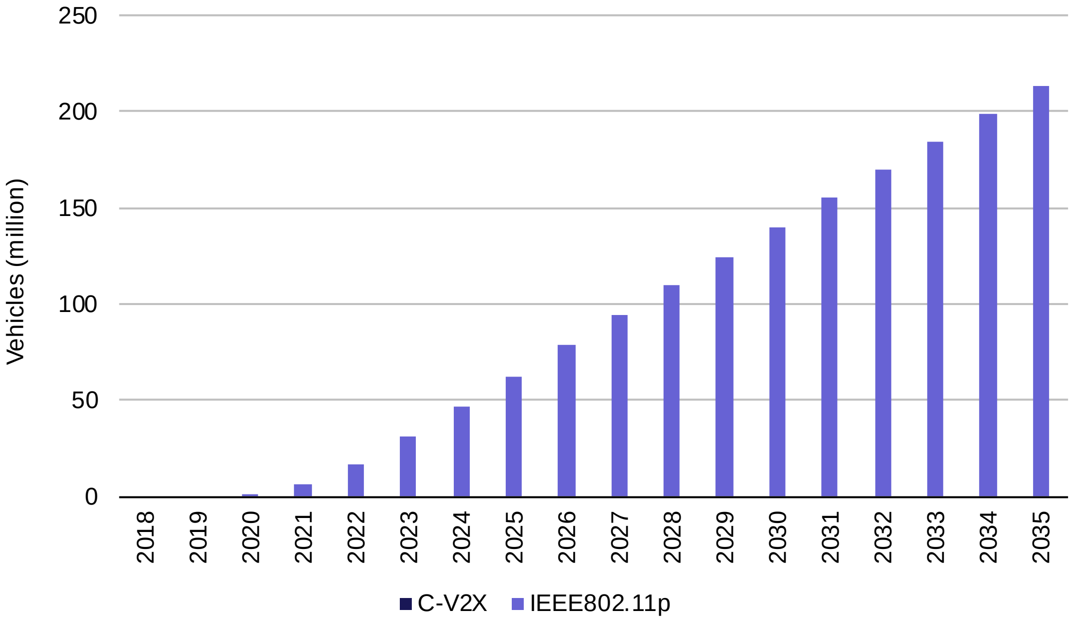
*Figure 5.19: Evolution of the net benefits in Scenario 1, by technology [Source: Analysys Mason, 2017]*



*Scenario 2 – 2020 EC mandate for V2V/V2I*

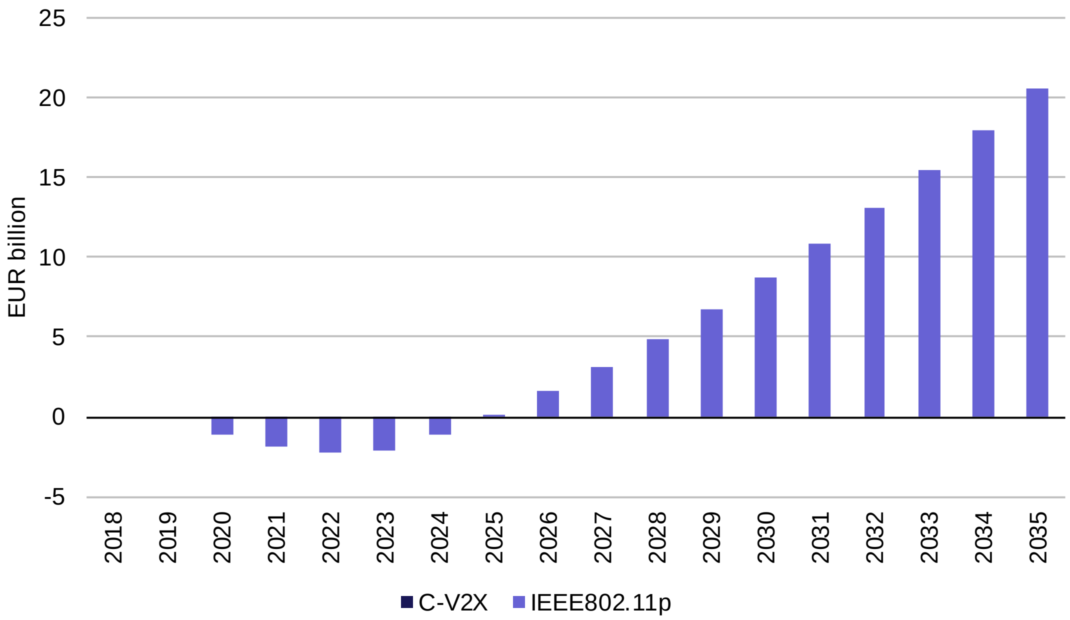
Overall, the number of vehicles equipped with embedded V2X services is expected to increase at a relatively fast pace under Scenario 2, as the EC mandate would force all automotive OEMs to equip all their new vehicle models with IEEE 802.11p from 2020. We assume a ramp-up period of four years for OEMs to implement V2X in all their new vehicles. In this scenario, no additional benefits would be generated by vehicles without a IEEE 802.11p interface, as smartphone vendors would be unlikely to include an IEEE 802.11p transceiver in their devices. Even if smartphone manufacturers did include a PC5 transceiver in smartphones, this would not be able to communicate with IEEE 802.11p-based RSUs. Figure 5.20 provides an overview of the number of vehicles using V2X services in Scenario 2.

*Figure 5.20: Evolution of the number of vehicles using V2X services in Scenario 2, by technology [Source: Analysys Mason, 2017]*



Net benefits are expected to exceed EUR20 billion by 2035 (see Figure 5.21 below). The addition to roadside infrastructure with IEEE 802.11p RSUs to support V2I communications is expected to generate significant costs. While we assume this would take place between 2020 and 2023, in practice this timeframe could prove optimistic – without an incentive to deploy RSUs, road operators would opt to deploy these over a longer timeframe, in line with replacement cycles for existing roadside infrastructure (which can be quite long).

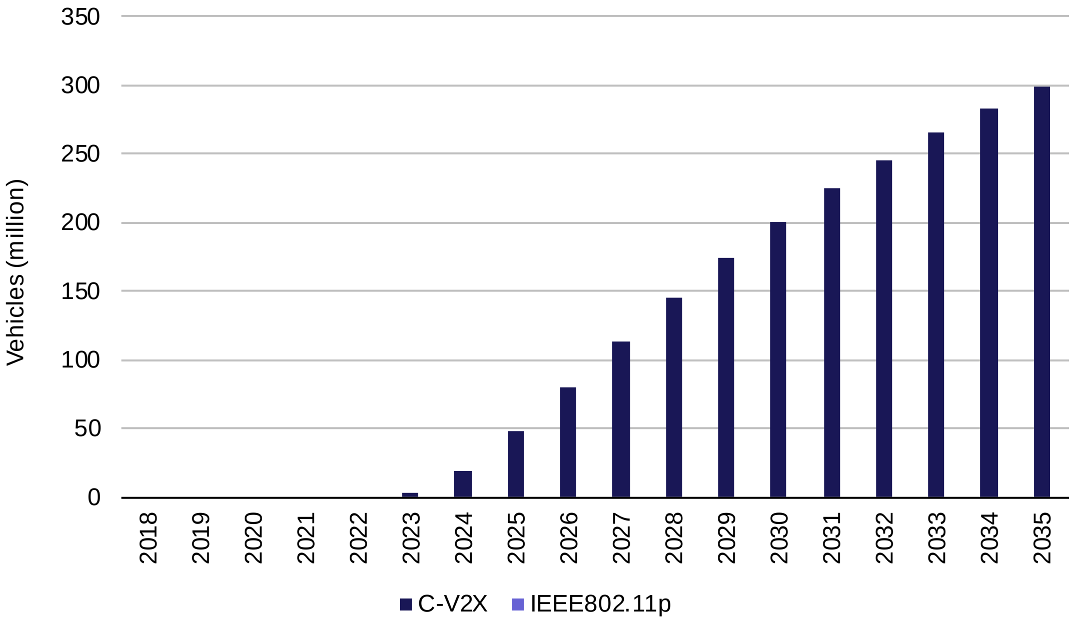
*Figure 5.21: Evolution of the net benefits in Scenario 2, by technology [Source: Analysys Mason, 2017]*



*Scenario 3 – 2023 EC mandate for V2V/V2I*

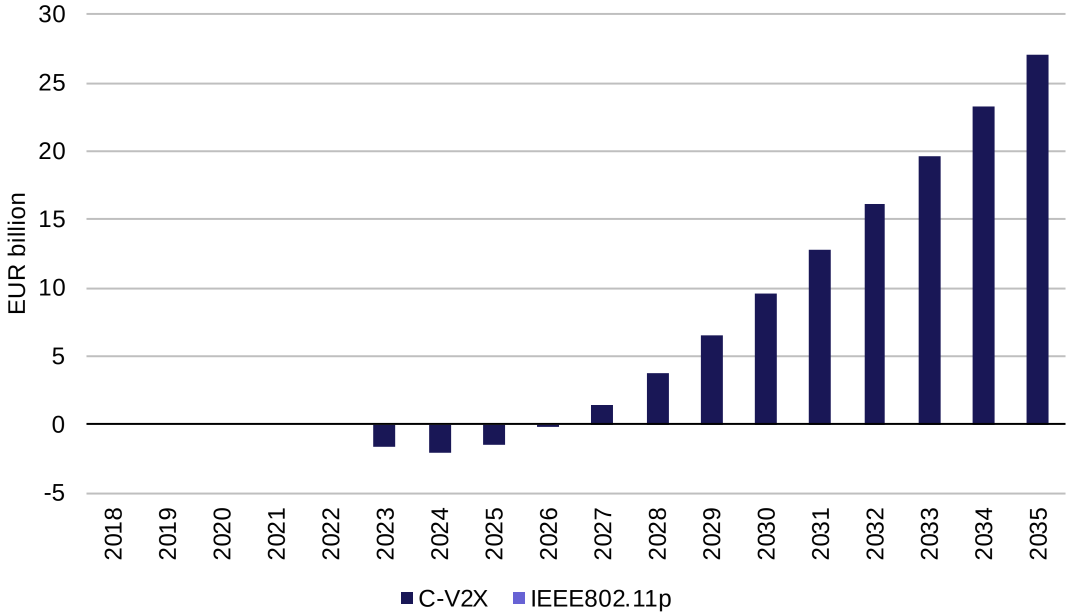
As in Scenario 2, the number of vehicles equipped with an LTE PC5 interface is expected to rise relatively quickly (see Figure 5.22), as an EC mandate would require all automotive OEMs to fit all their new vehicle models with a PC5 chipset from 2023 onwards. In contrast to Scenario 2, we have assumed a ramp-up period of only three years, to reflect the expected stronger readiness of C-V2X technology (due to the slightly later launch date). In this scenario, V2X penetration would be supported by the adoption and use of PC5-based smartphones by vehicles without an embedded PC5 interface, in order to access some V2I and V2P services.

*Figure 5.22: Evolution of the number of vehicles using V2X services in Scenario 3, by technology [Source: Analysys Mason, 2017]*



Net benefits in Scenario 3 are expected to reach around EUR27 billion by 2035 (see Figure 5.23). The addition to existing roadside infrastructure of IEEE 802.11p RSUs to support V2I communications would generate significant initial costs in the first few years of the forecast period, but the stronger PC5/Uu chipset integration and greater economies of scale generated would incur lower overall costs than in Scenario 2. Combined with the additional benefits generated from the use of V2I/V2P services by PC5-based smartphones, this would shorten the time required to achieve breakeven compared to Scenario 2.

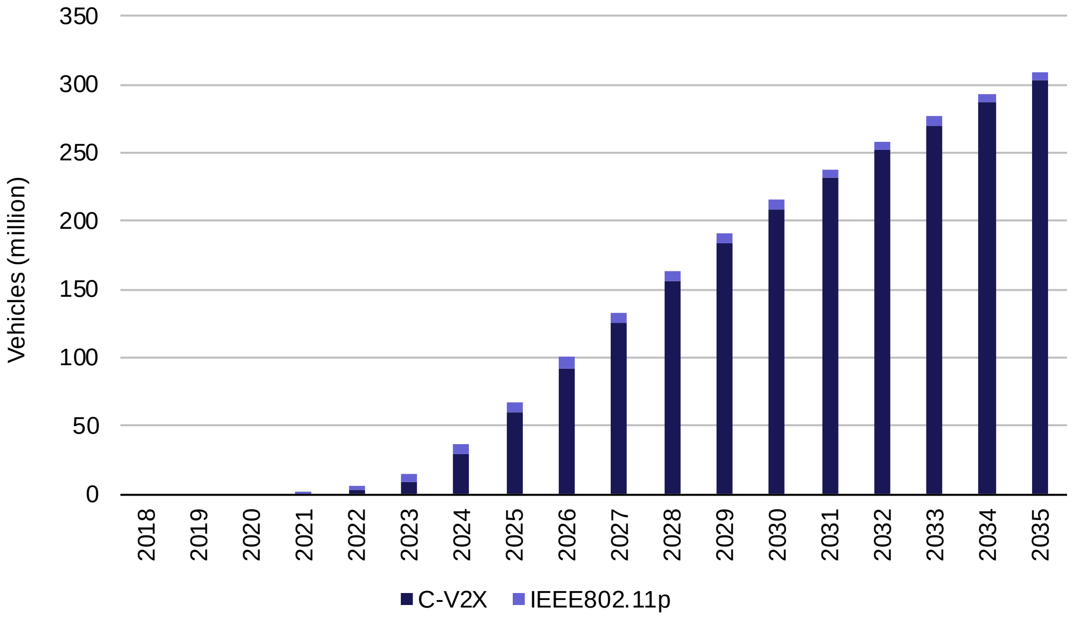
*Figure 5.23: Evolution of the net benefits in Scenario 3, by technology [Source: Analysys Mason, 2017]*



*Scenario 4 – equitable 5.9GHz use*

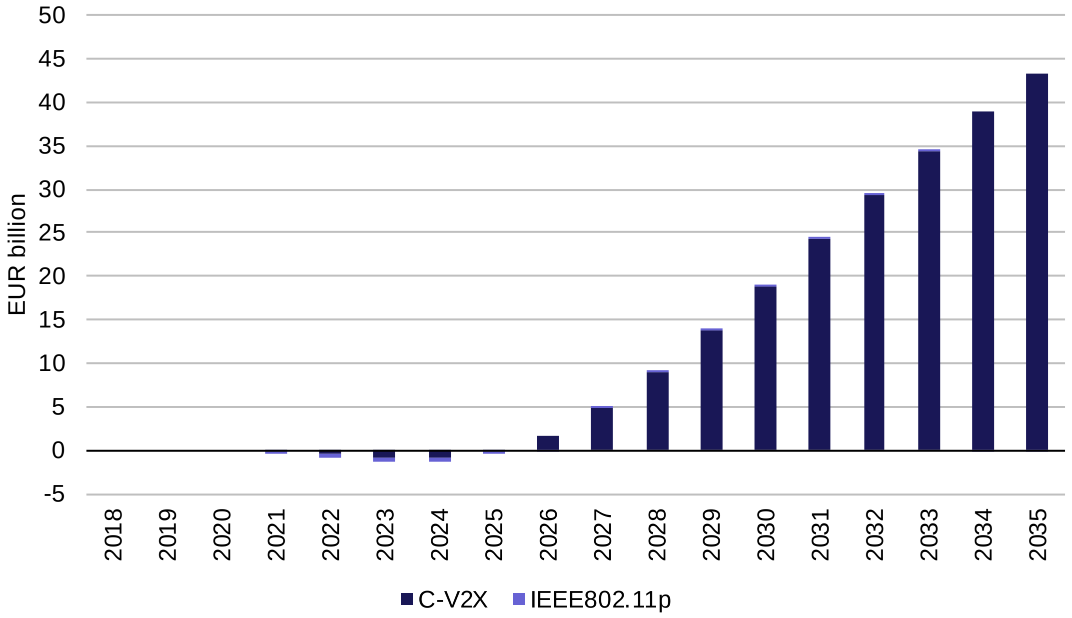
Overall, the evolution of the number of vehicles equipped with an embedded IEEE 802.11p or PC5 interface is expected to be similar to Scenario 1 (see Figure 5.24 below). However, the co-existence solution would increase confidence in PC5 in Scenario 4, providing a slight boost to the overall adoption of V2X. Over time the adoption of V2X is expected to expand to a greater number of vehicle models and will be supported by the adoption and use of PC5-based smartphones by vehicles that do not have an embedded V2X interface, in order to access some V2I and V2P services. In this scenario, the greater confidence in PC5 would increase the PC5 share of vehicles sold with V2X services, compared to Scenario 1. V2I/V2N services would be provided via MNOs' networks.

*Figure 5.24: Evolution of the number of vehicles using V2X services in Scenario 4, by technology [Source: Analysys Mason, 2017]*



Net benefits are expected to reach over EUR43 billion in 2035 in this scenario (see Figure 5.25 below). This is a higher level of net benefits than in Scenario 1, as Scenario 4 has a larger number of vehicles equipped with V2X services and a slightly greater share of vehicles using actuation services. Again, the C-V2X share of net benefits is expected to be larger than its share of the number of vehicles using V2X services, as the unitary impact per vehicle equipped with C-V2X is expected to be larger than for IEEE 802.11p (due to ‘network effects’).

*Figure 5.25: Evolution of the net benefits in Scenario 4, by technology [Source: Analysys Mason, 2017]*



## 5.3 Employment impact

Our modelling of the benefits of C-ITS systems quantified the cost savings generated across four broad categories of impact (road accidents, fuel consumption, $CO_2$ emissions and time spent on the road). However, other categories of impact can be considered and assessed quantitatively and qualitatively. One such category is the impact on the creation of new jobs – both new jobs in the automotive industry to support the deployment of C-ITS systems (e.g. hardware design, manufacturing, deployment, installation, maintenance, operation) and jobs created indirectly in other industries:

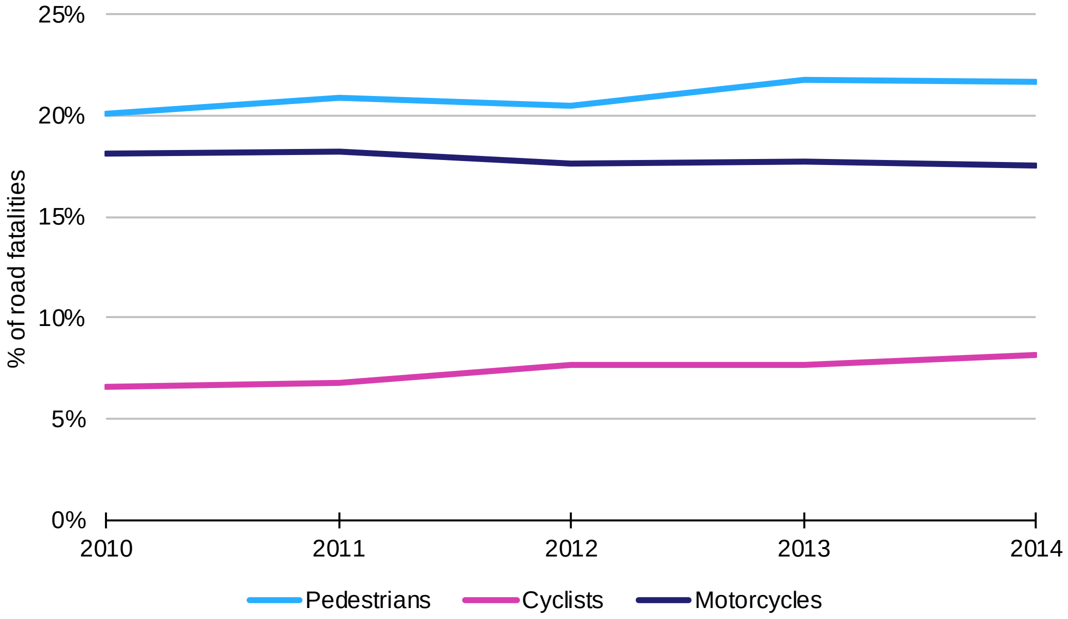
- **New *direct* jobs** have been estimated by calculating the change in the number of FTEs required to address the annual costs of deployment of C-ITS system. Our literature review suggests an average change in full-time equivalent employees of around 9.5–10 per EUR1 million output for the automotive industry
- **New *indirect* jobs** have been estimated by multiplying the number of new direct jobs created by an employment multiplier. Our literature review suggests that an employment multiplier of 2.4–2.5 is appropriate for the automotive industry.

Based on these assumptions, we estimate that the number of additional direct and indirect jobs created by 2030 due to the deployment of C-ITS systems would be in the range 190 000–220 000.

### 5.3.1 Other relevant impacts

Many of the C-ITS services deployed in the four scenarios we modelled aim to improve safety and reduce both the frequency and severity of accidents. A large percentage of fatal road accidents currently involve vulnerable road users. As of 2014 (latest available data), vulnerable road user fatalities (pedestrians, cyclists, motorcycles) amounted to more than 12 000 and accounted for over 47% of total road fatalities, up from 45% in 2010. This increase was mainly driven by the pedestrian segment, whose share increased from 20% to 22% over the same period (see Figure 5.26).

*Figure 5.26: Share of road fatalities by vulnerable road user segment [Source: European Commission, 2017]*



An overall improvement in road safety is therefore likely to have a positive impact on the safety of vulnerable road users. V2P services specifically aim to protect pedestrians, cyclists and motorcyclists. Our estimate is that V2P services alone could prevent around 3000 accidents involving pedestrians or cyclists (0.3% of total road accidents) by 2035 in the EU.

Other relevant impacts of C-ITS systems that were not quantified in our modelling include:

- ***Impact on job quality***. Workers who use vehicles to carry out their duties (e.g. taxi drivers, bus drivers, truck drivers) are likely to benefit from V2X services in various aspects of their job, in the form of improved comfort of travel (traffic efficiency, safety), reduced total working time (traffic efficiency), additional income (e.g. extra bonuses for reduced travelling time), etc.

- ***Impact on SMEs***. The deployment of C-ITS systems is expected to generate new revenue opportunities for the supply side. In particular, SMEs are expected to play a role in the installation and operation of C-ITS systems. From a demand perspective, SMEs are expected to benefit from cost reductions driven by improved traffic efficiency and reduced fuel consumption. However, the adoption of C-ITS systems is likely to take more time for SMEs than for consumers or even large enterprises, as SMEs tend to allocate their resources more cautiously than large enterprises and so are more likely to buy second-hand commercial vehicles rather than new ones.

# 6 Conclusions and recommendations

## 6.1 Conclusions

The research conducted for this study, combined with our modelling results, suggests that the deployment of C-ITS systems is beneficial at the EU level. Net benefits that could be accrued in Europe are estimated to be in the range of EUR20 billion to EUR43 billion in 2035, across the four scenarios modelled.

Several conclusions can be drawn from the modelling results:

- ***Most benefits are expected to be generated from increased road safety and traffic efficiency***. The largest contributors to monetised benefits are a reduction in time spent on the road (i.e. due to less time being wasted, which generates 80% of benefits generated in 2035 in Scenario 1) and a reduction in accident rates (17% of benefits in Scenario 1). Together, they account for over 97% of total benefits generated in Scenario 1, while the benefits from reduced fuel consumption and $CO_2$ emissions are negligible.

- ***The base case and equitable 5.9GHz use scenarios, without an EC mandate requiring 5.9GHz RSU deployment, and encouraging PC5-based V2V take-up, appear to be the most beneficial way to deploy C-V2X services, from a net benefit perspective.*** Although Scenarios 2 and 3 achieve positive net benefits in the long run, the investment required to add to roadside infrastructure with 5.9GHz V2I RSUs means it takes longer to achieve breakeven than in Scenarios 1 and 4, where the re-use of cellular networks to provide V2N reduces costs significantly, and also allows high infrastructure penetration from day 1 (resulting in benefits from V2I/V2N services being realised sooner).

- ***Additional benefits from C-V2X can be achieved if LTE PC5 communication is integrated into future smartphones.*** In Scenarios 1, 3 and 4, the ability for vehicles without an embedded PC5 or IEEE 802.11p interface to access V2I/V2P communications via a compatible PC5 or IEEE 802.11p smartphone can lead to further increases in both the penetration, the unitary benefit per vehicle and the overall benefits generated. In particular, the increase in the unitary benefit per vehicle is due to the 'network effect' of having a larger number of vehicles equipped. For example, in Scenario 2, the unitary impact per passenger car equipped with warning and information services in 2035 is a 16.6% reduction in the number of accidents per billion kilometres on motorways (based on 24% of vehicles having access to V2I services); in Scenario 1, additional vehicles without a direct communications interface that use a smartphone to access some V2I/V2P services help to increase V2I penetration to over 70% of vehicles and boost the overall unitary road safety benefit per passenger car equipped with warning and information services to 19.3%.

- ***Most costs are expected to be incurred by in-vehicle C-ITS systems***. In the scenarios involving EC mandates for V2V/V2I (Scenarios 2 and 3), the requirement for all new vehicle types to have

C-ITS systems means that in-vehicle costs account for over 85% of cumulative costs over the modelling period, with the remaining costs being related to the roll-out of PC5/IEEE 802.11p-based RSUs. It is noted that any regulatory requirement to support interoperability between IEEE 802.11p and PC5-based systems would increase in-vehicle costs further. For example, if an automotive OEM that wished to equip a vehicle with V2V communications needed to install both PC5 and IEEE 802.11p for interoperability reasons, the in-vehicle costs would be significantly increased. This is due to the additional radio frequency components (i.e. chipsets and antennas), as well as the increased cost of integrating both solutions into vehicle telematic or other control units, since it is not technologically feasible for the two V2V radio systems (IEEE 802.11p and C-V2X PC5) to communicate with each other.[53] Our view, based upon research for this study, is that the additional costs of supporting dual technologies for V2V to provide interoperability between all vehicles would be high relative to the available evidence on the benefits that would be gained.

## 6.2 Recommendations

Based on the results of this study, we have identified the following recommendations.

| | |
|---|---|
| *European C-ITS policy should support synergies between the two modes of C-V2X communication, and with the wider ecosystem of 3GPP-based infrastructure already deployed by mobile operators* | Several modes of C-V2X communication offer a potential for technology integration between V2V/V2I and existing cellular network (i.e. using V2N), with resulting cost–benefit advantages.<br>Our modelling Scenarios 1 and 4 – base case and equitable 5.9GHz use, without an EC mandate requiring 5.9GHz RSU deployment, and encouraging PC5-based V2V take-up – appear to be the most beneficial in terms of deploying V2X services, since the estimated net benefits from these scenarios are highest.<br>Although Scenarios 2 and 3 (involving EC mandates for V2V/V2I) achieve positive net benefits over the long run, the investment required to add to roadside infrastructure means that it takes longer to achieve breakeven than in Scenarios 1 and 4, where the re-use of cellular networks to provide V2N services reduces costs and allows high infrastructure penetration from service launch. It is assumed that mobile operators would work with road operators to facilitate C-V2X solutions, for example by providing the required data (subject to data-protection requirements) so that V2V/V2I could occur in the same timeframe.<br>We also note that an extended roll-out period for V2I (e.g. relying on road operators to add to existing roadside infrastructure) would mean |

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[53] A mandate from the Radio Spectrum Committee (RSC) to the Conference of Postal and Telecommunication Administrations (CEPT) in October 2017 to study extension of the ITS-safety related spectrum at 5.9GHz recognises that the two V2V systems (IEEE 802.11p and C-V2X PC5) cannot communicate with each other.

| | |
|---|---|
| | that the full capabilities of V2X were not available, thus reducing and/or delaying the benefits achieved. |
| *Migration towards 5G-based V2X should be encouraged, in line with market demand* | The migration from 4G to 5G technology will take some time to implement, but should provide a significant capacity increase and improved network flexibility. This future evolution path provides backward compatibility with previous generations of 3GPP technology, and is a key benefit of C-V2X.<br>Mobile operators are widely expected to upgrade current 4G networks from around 2020 onwards, in line with market demand for 5G. This migration will potentially create opportunities for new commercial business models around 5G-based V2X (and integration with smart cities, and other connected services that also use 5G), as well as reducing the cost of V2I roll-out, by using mobile networks for V2N where possible.<br>As such, we recommend that European C-ITS policy should be designed to encourage migration from the current V2X technologies to 5G. |
| *V2P services deployed as part of C-V2X can provide additional benefits, and hence we recommend policies that encourage the development of PC5-enabled smartphones* | Most respondents to our primary research for this study thought it was unlikely that IEEE 802.11p chipsets will be integrated into smartphones in future. In contrast, they expressed more positive views that smartphones can be C-V2X-enabled, creating an opportunity for V2P services, as well as enabling vehicles without embedded C-V2X communication to use C-V2X-smartphones (i.e. ‘after-market devices’, in our analysis). V2P will benefit several categories of road user, including pedestrians, cyclists and motorcyclists. V2P will also be essential for vehicles to be fully automated on urban roads (e.g. to identify when to stop at a non-signalised crossing if a pedestrian is approaching). |

# Annex A Abbreviations and terms used in this report

| Term | Description |
|---|---|
| 3GPP (Third Generation Partnership Project) | The Third Generation Partnership Project is a collaboration involving seven international standards organisations which produce reports and specifications for radio communications technologies. |
| 4G | 4G refers to the fourth generation of broadband radio network technologies. In the context of this report, 4G includes both LTE and LTE-A technologies. |
| 5G | 5G refers to the fifth generation of broadband radio network technologies. |
| 5GAA (5G Automotive Association) | The 5G Automotive Association is a Market Representation Partner to the 3GPP which provides market advice and a view of market requirements for the automotive industry. |
| ADAS (advanced driver-assistance systems) | An advanced driver-assistance system uses technologies such as sensors, cameras and radar to improve the driving experience, safety and transport efficiency. |
| AEB (advanced emergency braking) | An advanced emergency braking system uses ADAS technologies to assess the likelihood of a collision and apply the brakes automatically, to either avoid or mitigate the consequences of a crash. |
| C-ITS (cooperative intelligent transport systems) | Cooperative intelligent transport systems are the technologies that allow for V2X communications, as defined by the EC. |
| C-V2X (cellular V2X or cellular vehicle-to-everything) | C-V2X refers to the provision of V2X using standards developed by the 3GPP based on wireless telecommunications technologies (namely 4G-LTE and upcoming 5G-NR). C-V2X incorporates communications made via Uu connectivity and the PC5 interface. |
| C-V2X ‘PC5 mode 3’ | Mode 3 refers to the PC5 configuration of C-V2X which allows the edge of the cellular network to assist in the radio resource management of V2V communication. |
| C-V2X ‘PC5 mode 4’ | Mode 4 refers to the PC5 configuration of C-V2X which allows vehicles to manage V2V communications traffic for radio resource management using an algorithm distributed among vehicles. This mode is implemented *without* the support of the Uu interface. |
| CACC | Cooperative adaptive cruise control |
| DSRC (direct short-range communications) | Direct short-range communications, or WAVE, is the IEEE 802.11p-based V2X solution under development in the USA. |
| ETC (electronic tolling collection) | An electronic tolling collection system enables automated collection of tolls from moving or stopped vehicles, via short-range wireless technologies. |
| EU (European Union) | The political and economic union of European member states. |
| GNSS (global navigation satellite system) | A system that uses satellite to provide autonomous geo-spatial positioning. |
| IEEE 802.11p | IEEE 802.11p is a Wi-Fi standard developed by the Institute of Electrical and Electronics Engineers (IEEE), for the provision of V2X. IEEE 802.11p specifically provides direct, short-range communications (e.g. V2V, V2I and V2P) and is used as the |

| Term | Description |
|---|---|
| | basis for several technologies, such as WAVE or DSRC in the USA, ITS-G5 in Europe and ITS Connect in Japan. |
| IoT (Internet of Things) | The Internet of Things refers to the use of connected devices and systems to leverage any data collected. |
| ITS (intelligent transport system) | The EC defined ITS in Directive 2010/40/EU as advanced applications to provide innovative services to different modes of transport and traffic management.<br>ETSI has produced many standards for the ITS communications protocol stack (not to be confused with ITS-G5, which is the access layer of the protocol stack and based on the IEEE 802.11p Wi-Fi standards). |
| MNO (mobile network operator) | A mobile network operator is a company that provides wireless communications services with control over the necessary radio equipment or infrastructure. |
| NHTSA (US National Highway Traffic Safety Administration) | A department of the US DoT responsible for vehicle safety standards, regulations and protocols, as well as vehicle manufacturing and importing licences. |
| OEM (original equipment manufacturer) | An original equipment manufacturer is a company that produces parts or equipment marketed by other companies.<br>In the context of this report OEM refers to an automotive OEM, which manufactures vehicles. |
| PC5 | PC5 is an interface for direct, short-range communications between entities. |
| Roadside infrastructure | Roadside infrastructure includes any installed roadside equipment that conveys information to passing drivers (such as traffic signals and road signs). |
| RSU (roadside unit) | A roadside unit is a communications unit that is capable of V2X communications, specifically V2I and V2N2I, and that may be connected to roadside infrastructure. |
| US DOT | The US Department of Transportation is a federal department of the US government, responsible for transportation matters. |
| Uu | Uu is an interface for communications between an entity and a base station across a telecoms network. |
| V2I (vehicle-to-infrastructure) | V2I refers to direct communications between a vehicle and roadside infrastructure. The roadside infrastructure must be connected with an RSU to enable V2I. |
| V2N (vehicle-to-network) | V2N refers to communications between a vehicle and ICT infrastructure, such as an application server, across a mobile telecoms network. |
| V2N2I (vehicle-to-network-to-infrastructure) | Vehicle-to-network-to-infrastructure refers to indirect communications between a vehicle and roadside infrastructure. Similar to V2I communications, however the mobile network is used as an intermediary. |
| V2N2P (vehicle-to-network-to-pedestrian) | Vehicle-to-network-to-infrastructure refers to indirect communications between a vehicle and pedestrians. Similar to V2P communications, however the mobile network is used as an intermediary. |
| V2N2V (vehicle-to-network-to-vehicle) | Vehicle-to-network-to-vehicle refers to indirect communications between vehicles. Similar to V2V communications, but the mobile network is used as an intermediary. |

| Term | Description |
|---|---|
| V2P (vehicle-to-pedestrian) | V2P refers to direct communications between a vehicle and pedestrians. |
| V2V (vehicle-to-vehicle) | V2V refers to direct communications between vehicles. |
| V2X (vehicle-to-everything) | V2X refers to communications between a vehicle and a second entity (which may include other vehicles, road infrastructure, network infrastructure and pedestrians). V2X communications may be categorised by the second entity involved (V2V, V2N, V2I, etc.).<br>V2X communications can be used to provide a range of services (e.g. cooperative collision warning or CACC). |
| WAVE (Wireless Access for Vehicular Environments) | Wireless Access for Vehicular Environments, or DSRC, is the IEEE 802.11p-based V2X solution under development in the USA. |

# Annex B Modelling approach and supplementary results

## B.1 Overview of modelling approach

When quantifying the costs and benefits of C-V2X in the EU we considered the time period from 2018 to 2035. We combined primary and secondary research (conducted using telephone interviews and questionnaires issued to 5GAA member companies) to derive assumptions for our quantitative modelling.

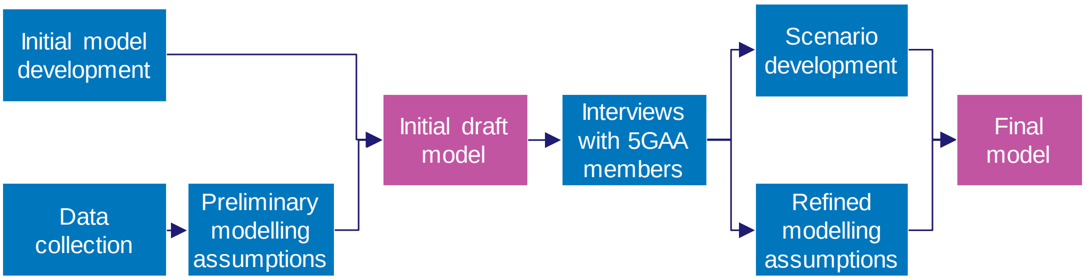
We first conducted extensive desk research to inform key modelling assumptions and to develop an initial draft model. Key data sources included industry reports, press releases, third-party studies and internal materials.

We supplemented this research by conducting interviews with almost 25 5GAA members. The interviews included a series of questions to help us understand development timelines, costs and deployment assumptions for V2V, V2N and V2P technologies within the overall V2X communications service offering.

We used the information collected to refine and update our modelling assumptions, validate our initial understanding of C-V2X developments and define a series of modelling scenarios based on alternative penetration assumptions for C-V2X and IEEE 802.11p.

Figure B.1 below provides a summary of our modelling approach.

*Figure B.1: Overview of modelling approach [Source: Analysys Mason, 2017]*



## B.2 Supplementary results

*Benefits by category of impact*

The following figures illustrate the evolution of the benefits modelled by category, namely cost savings from a reduction in the number of accidents (Figure B.2), from lower fuel consumption (Figure B.3), from a reduction in $CO_2$ emissions (Figure B.4), and from a reduction in time spent on the road (Figure B.5).

*Figure B.2: Evolution of road safety benefits, by scenario [Source: Analysys Mason, 2017]*

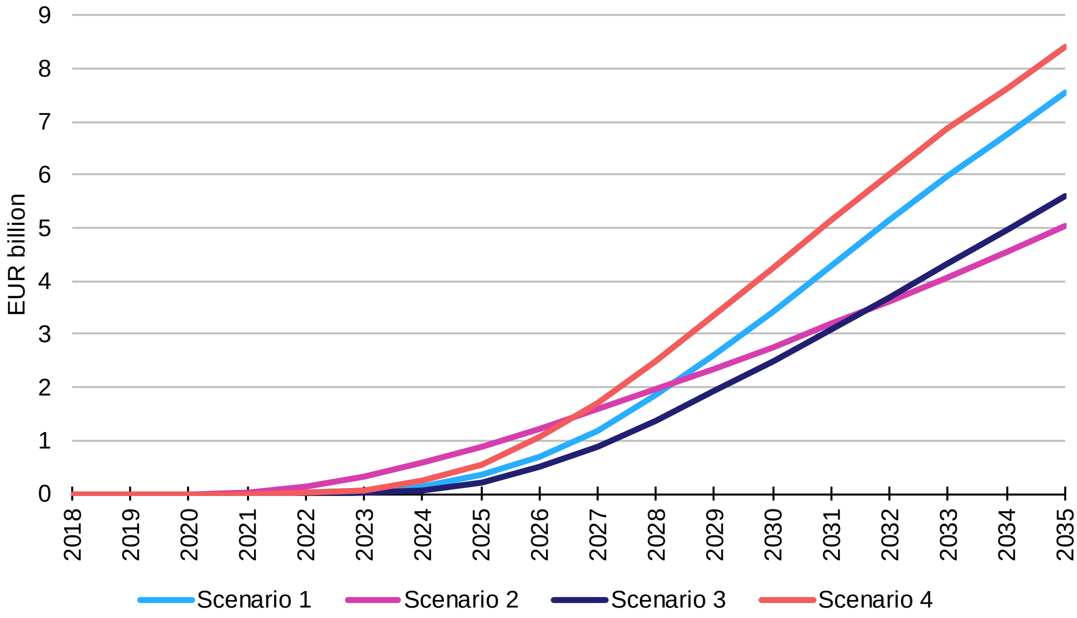


*Figure B.3: Evolution of fuel consumption benefits, by scenario [Source: Analysys Mason, 2017]*

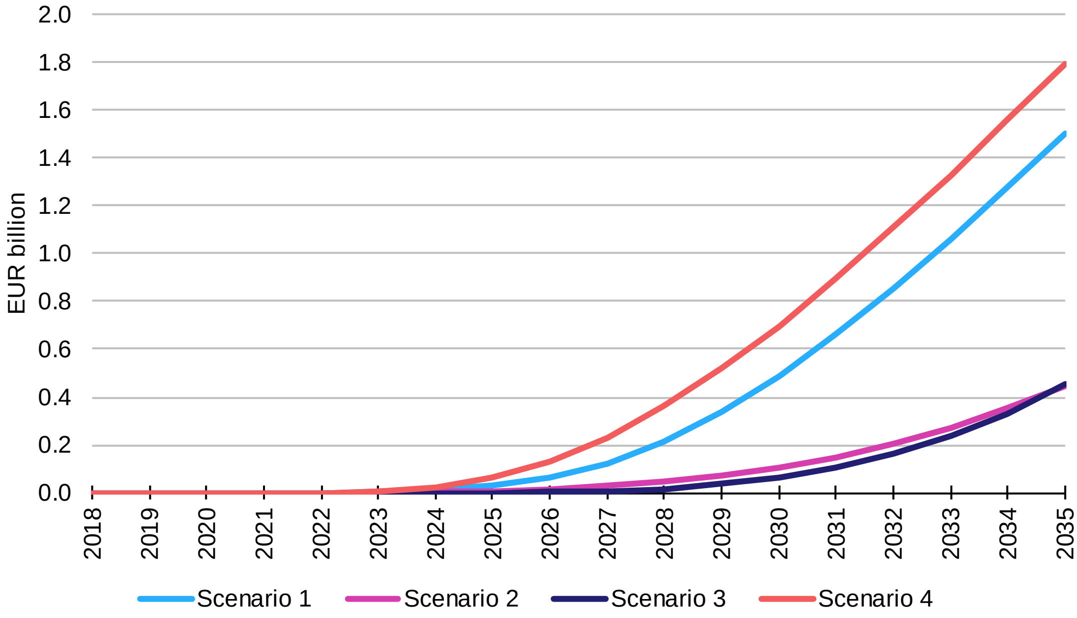


*Figure B.4: Evolution of $CO_2$ emissions benefits, by scenario [Source: Analysys Mason, 2017]*

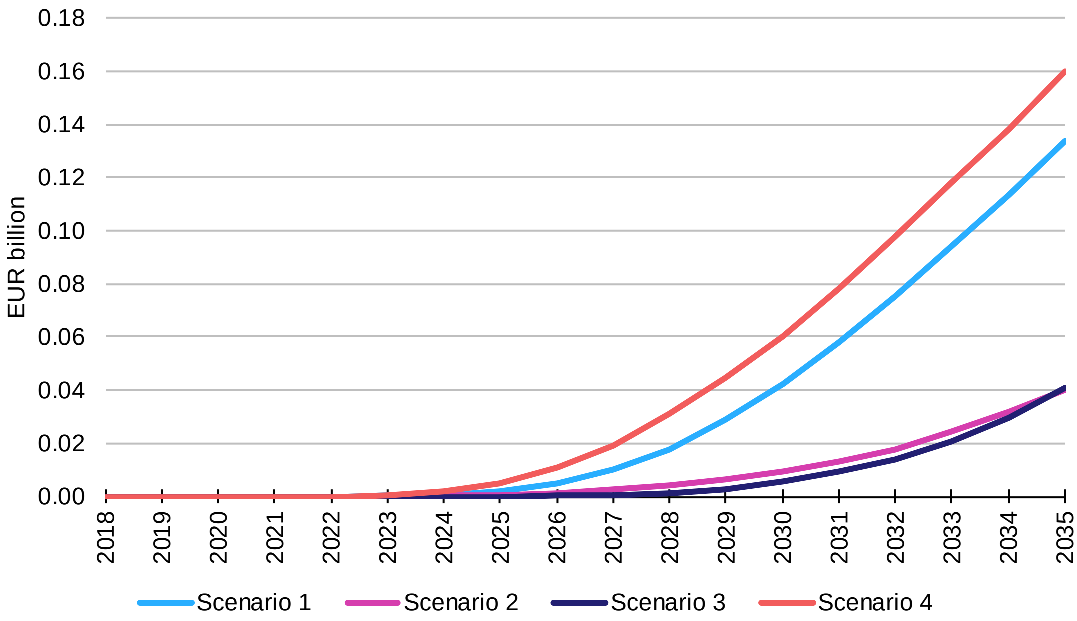
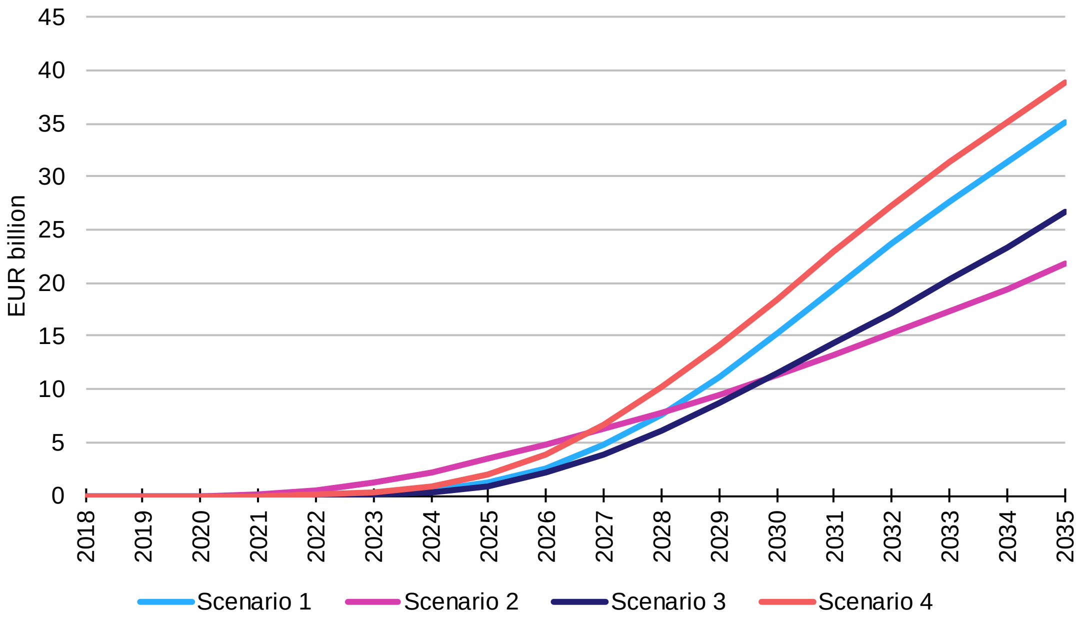


*Figure B.5: Overview of traffic efficiency benefits, by scenario [Source: Analysys Mason, 2017]*



### *Benefits by road type*

The following figures illustrate the evolution of the benefits accrued by road type modelled, namely urban roads (Figure B.6), rural roads (Figure B.7) and motorways (Figure B.8).

*Figure B.6: Benefits on urban roads, by scenario [Source: Analysys Mason, 2017]*

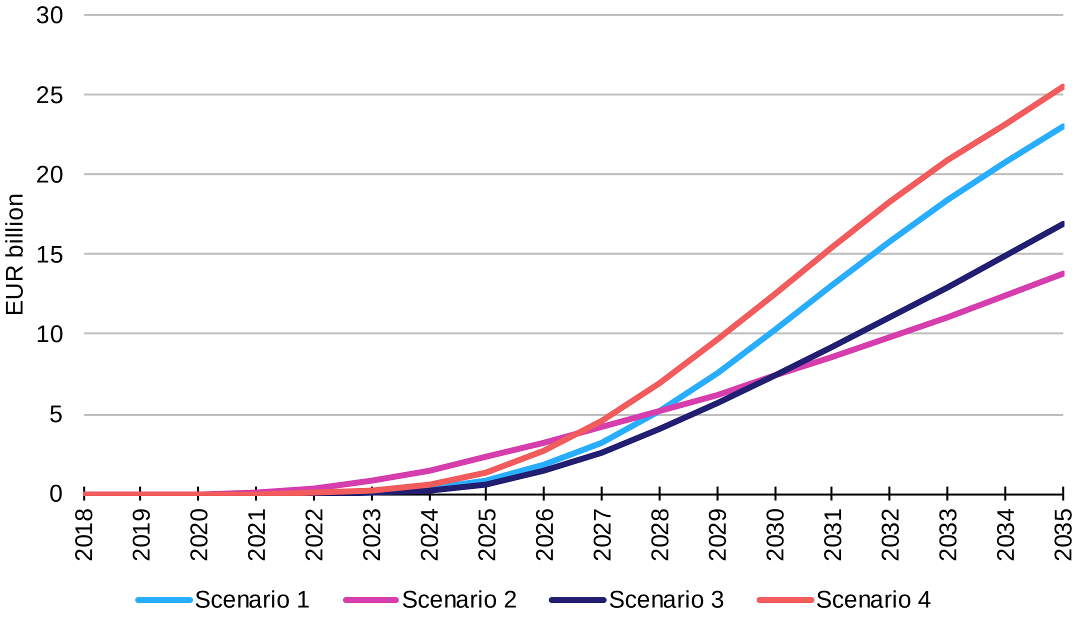


*Figure B.7: Benefits on rural roads, by scenario [Source: Analysys Mason, 2017]*

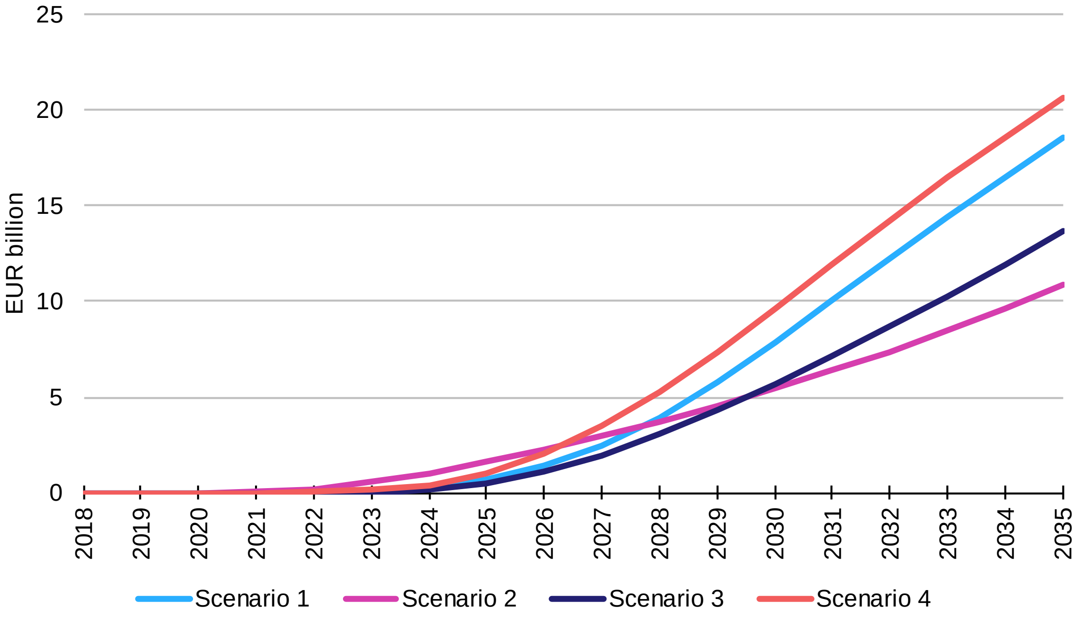
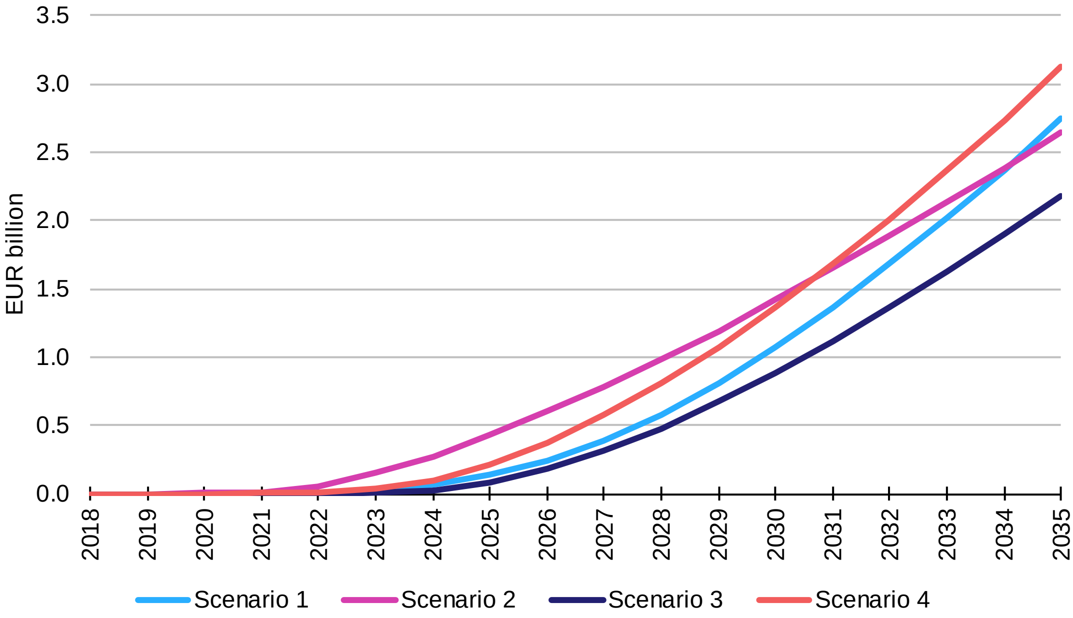


*Figure B.8: Benefits on motorways, by scenario [Source: Analysys Mason, 2017]*



# Annex C Summary of primary research for this study

This annex provides a summary of findings from the approximately 25 interviews that we conducted with individual 5GAA member companies as part of the study.

The interviews included a series of questions to help us understand development timelines for V2V, V2N and V2P technologies within the overall V2X communications service offering. During the interviews we sought to elicit the views of 5GAA members on the following areas:

- **Adoption and timing for V2X technologies**
  - When will the necessary specifications and standards (for cellular V2X) be ready?
  - Do you have a roadmap showing steps between now and the first launch of cellular V2X services?
  - When will compatibility/interoperability test requirements and certification procedures be ready?
  - What are the key challenges that still need to be overcome?
  - When will production-level chips be available?
  - When will the security infrastructure (digital certificates etc.) be up and running?
  - When will field testing be completed to prove theoretical performance, reliability, etc.?

- **Market penetration**
  - How likely is it that all / a group of automotive OEMs will ‘jump at once’ in terms of launching C-V2X?
  - What business models are expected? Can automotive OEMs charge for the technology?
  - How likely is it that the EC will mandate the fitment of V2X?
  - How likely are automotive OEMs to fit the technology as standard?

- **Technology readiness**
  - What is the status of security, privacy and related considerations for C-V2X?
  - What is the status of spectrum assignment and compatibility between different V2V technologies in the 5.9GHz spectrum?

- **Costs**
  - What is needed to add C-V2X (e.g. radio front-end, processing back-end, security, etc.)?
  - Where are messages to be analysed and warnings generated – in the telematic control unit (TCU) or in another electronic control unit (ECU)?
  - Will this make the TCU a safety-critical part? If so, what is the impact on cost?
  - Are there any requirements for an updated antenna to support C-V2X?
  - How much will security infrastructure cost and who will pay (e.g. digital certificates, blacklists)?
  - What is the cost impact of C-V2X on chipset/modem/TCU?

- **Benefits**
  - What output in terms of impact/benefit can we expect from the ongoing trials?
  - What are the key performance targets for C-V2X (reliability, latency, range, bandwidth attenuation, processing, interference, etc.)?
  - Which 3GPP releases (e.g. Release 14) are these targets aligned with?
  - How will performance vary with different road conditions (e.g. urban, rural, motorways)?
  - Under what conditions will C-V2X not work?
  - Other comments?

Some interviews were by phone, while other respondents provided written answers. It should be noted that the interviews were undertaken on the understanding that the feedback provided would not be attributed to individual interviewees. Instead we have grouped the interview findings according to the topic headings listed above.

The list of companies that agreed to take part in interviews for this study is shown in Figure C.1 below, together with the status of each interview.

*Figure C.1: Status of interviews [Source: Analysys Mason, 2017]*

| Stakeholder | Role in 5GAA | Replied? | Interview status | Comments |
|---|---|---|---|---|
| AT&T | Board member | Yes | Complete | |
| Audi | Board member | Yes | Complete | |
| BMW | Board member & working group (WG) | Yes | Complete | |
| China Mobile | Board member | Yes | Complete | |
| Daimler | Board member | Yes | Complete | |
| Denso Automotive | Member | Yes | Complete | |
| Ericsson | Board member & WG lead | Yes | Complete | |
| Ford | Board member & WG lead | Yes | Complete | |
| Huawei | Board member & WG lead | Yes | Complete | |
| Intel | Board member & WG lead | Yes | Complete | |
| JLR | Board member | Yes | - | |
| LG Innotek | Member | Yes | Complete | |
| Nokia | Board member & WG lead | Yes | Complete | |
| NTT DOCOMO | Board member | Yes | Complete | |
| Qualcomm | Board member & WG lead | Yes | Complete | |
| SAIC | Board member | Yes | Complete | Written response provided |
| Samsung | Board member & WG lead | Yes | Complete | |

| Stakeholder | Role in 5GAA | Replied? | Interview status | Comments |
|---|---|---|---|---|
| Vodafone | Board member & WG lead | Yes | Complete | |
| Volkswagen | Member | Yes | Complete | |

The remainder of this annex summarises the feedback provided under the key topic areas above, and incorporates useful comments from the interviewees.

## C.1 Adoption and timing

*When will the necessary specifications and standards (for cellular V2X) be ready?*

Interviewees agreed that the necessary specifications for the radio interfaces for C-V2X were completed in the Release 14 specifications. This includes the PC5 interface for LTE direct mode (V2V), and the Uu interface for connectivity between vehicles and cellular networks. Additional activity to incorporate C-V2X within the ITS protocol stack was underway and would be completed in 2018, but this should not prevent the technology development (chipsets, antennas, Release 14 software) being progressed for C-V2X commercialisation.

Interviewees also agreed that a key benefit of C-V2X compared to IEEE 802.11p is that technology and capabilities will evolve in line with the normal sequence of 3GPP releases. 3GPP Release 15 is the next release and will specify the new radio interface for 5G – new radio, or 5G-NR – along with further evolution of LTE. 3GPP Release 16 is expected to be the first of the 3GPP releases that will address 5G-NR C-V2X. In the meantime, LTE C-V2X addresses all the automotive industry requirements (and being part of the 3GPP specifications, can be considered as a stepping stone to 5G).

*Do you have a roadmap showing steps between now and the first launch of cellular V2X services?*

Timelines for commercial launch of C-V2X were described as follows:

- Specifications and standards work will complete in 2018 – namely work to complete the high-level protocols and integrate these with the ITS protocol stack.
- Testing and technology demonstrations will take place during 2018 using pre-commercial chipsets.
- Assuming availability of commercial chipsets in 2019, all components and hardware can be ready by late 2019 – one OEM is planning a product demonstration in 2019 and others will follow, after this date.
- Realistically, commercial-level vehicles will launch in 2020/2021. China could be the first country/region to launch C-V2X. It was suggested that the earliest commercial launch of C-V2X features might take place in the second half of 2019.

- Some MNOs have confirmed roadmaps for implementing the necessary software and network updates to enable Release 14 V2N features, and commented that many of the safety benefits of an ITS can be accomplished through this Release 14 Uu connectivity.
- C-V2X will have additional benefits for provision of V2P, which might be a necessary service for cars to be fully automated on urban roads (e.g. to stop at non-signalised pedestrian crossings if needed). Most interviewees were not confident that V2P communication will be achievable using alternative approaches (e.g. they considered it unlikely that IEEE 802.11p technology will be integrated into smartphones). Hence, C-V2X (assuming the C-V2X interface is integrated into future smartphones) will facilitate V2P.

*When will compatibility/interoperability test requirements and certification procedures be ready?*

Testing requirements are being defined and testing will occur in 2018/2019. Most interviewees expressed positive views that interoperability and compatibility testing for C-V2X will be completed successfully, given the extensive specification work that the 3GPP has undertaken to develop C-V2X standards.

*What are the key challenges that still need to be overcome?*

Key challenges include: possibility of an EC mandate in Europe that might restrict V2X technology choice to ITS-G5/IEEE 802.11p, potential fragmentation within the automotive industry on adoption of different V2V solutions, and a risk of unnecessary investment in short-range 5.9GHz roadside units for V2I (where cellular networks using the Uu interface can provide an ideal solution without needing to invest in substantial numbers of RSUs). Co-existence of V2V technologies in the 5.9GHz band was also noted as a key concern.

Many interviewees proposed a solution – which 5GAA is endorsing – whereby IEEE 802.11p and C-V2X V2V technologies can co-exist in the 5.9GHz band. This would involve assigning distinct 10MHz channels to each technology for initial deployment, thereby ensuring that both technologies can be deployed within the 5.9GHz band, and allowing the market to determine the best solution.

Concern regarding the viability of business models for V2V solutions for safety services alone was also noted, whereas C-V2X solutions (incorporating a wider range of services, including network-based infotainment via the Uu interface) potentially enabled a wider range of business models to be identified. Future ‘comfort and convenience’ services in connected and automated cars were identified as an opportunity for C-V2X technology to be fully exploited.

*When will production level chips be available?*

Pre-commercial chipsets for PC5 connectivity will be available in 2018.

One OEM suggested that its understanding was that an integrated chipset solution (combining both PC5 and Uu connectivity) would likely be completed by one chipset provider by 2019 and available commercially from 2020.

MNOs noted that many automotive OEMs are looking to support C-V2X instead of DSRC/ITS-G5, because they expect a single chipset solution that integrates Uu connectivity with the PC5 interface. This will open up additional business models and opportunities for monetising technology investment beyond V2V services alone. The availability of an integrated chipset should encourage wider C-V2X adoption by automotive OEMs.

*When will the security infrastructure (digital certificates etc.) be up and running?*

Security infrastructure to support PC5 is currently being defined and should be ready in 2018. Security features in cellular networks can be used to support Uu connectivity.

*When will field testing be completed to prove theoretical performance, reliability, etc.?*

Most automotive OEMs expect that field testing to demonstrate C-V2X functionality will take place during 2018 and 2019. Upgrades to existing LTE infrastructure to implement the 3GPP Release 14 Uu capabilities can happen relatively quickly once market demand is established, and this has already been completed in some regions (e.g. China).

## C.2 Penetration

*How likely is it that all / a group of automotive OEMs will 'jump at once' in terms of launching C-V2X?*

Automotive OEMs will not all 'jump at once' to launch C-V2X, but adoption will proceed according to the automotive OEMs' own timescales. Launch could be phased across different new vehicle types – either starting from premium vehicles (to maximise opportunities for 'comfort and convenience' services to be offered), or by starting from cheaper vehicles (to rapidly build penetration and economies of scale). The wider benefits from using V2N connectivity for communication between vehicles and networks are expected to be a more compelling proposition for some automotive OEMs, who felt that V2V communication on its own did not justify the investment needed for in-car technology. There is the potential for automotive OEMs to implement C-V2X very quickly, given the involvement of automotive OEMs in the 5GAA, and the 5GAA's objective of building consensus.

*What business models are expected? Can automotive OEMs charge for the technology?*

Various automotive OEMs favoured business models incorporating wider C-V2X services such as comfort and convenience features in vehicles, infotainment, traffic information, real-time mapping, telematics and data analytics. Some MNOs suggested that commercial V2X services to connected vehicles offer a huge opportunity for MNOs and automotive OEMs, allowing partnerships to develop to take data from vehicles and undertake network-based data analytics, which would be paid for by the vehicle owner. These data analytic services may include data analytics gathered from services delivered across both Uu connectivity and the PC5 interface.

*How likely is it that the EC will mandate the fitment of V2X?*

Mixed opinions were expressed on the likelihood of an EC mandate for fitment of V2X, however many interviewees were concerned that a mandate could unintentionally push the market towards wider adoption of IEEE 802.11p, to the detriment of C-V2X. Most agreed that any mandate should be technology neutral and that the EC should focus on future-proofing ITS technology (enabling a smooth evolution to 5G) rather than forcing early adoption. China was likely to be the first market to adopt C-V2X and the regulatory environment in China is positive for C-V2X deployment.

*How likely are automotive OEMs to fit the technology as standard?*

Most believe that C-V2X will eventually be implemented as a standard feature in vehicles. The automotive industry is promoting safety features very strongly, and C-V2X will be implemented more widely, offering additional services, once the C-V2X technology and 5G services become more common. Those vehicles that do not implement the technology may then come to be regarded as less competitive in the market.

## C.3 Technology readiness

*What is the status of security, privacy and related considerations for C-V2X?*

Most interviewees considered that security and privacy considerations of V2X services have already been established for DSRC/ITS-G5 technologies and much of this work is expected to be reused for the implementation of C-V2X.

*What is the status of spectrum assignment and compatibility with DSRC?*

The operation of C-V2X and DSRC/ITS-G5 or IEEE 802.11p in the same channels in the 5.9GHz band will degrade the performance of both technologies through co-channel interference. The additional cost of having to support both PC5 and IEEE 802.11p in the same vehicle was also likely to be unacceptable. Equitable use of 5.9GHz spectrum and management of the frequency band were described as crucial to the success of both IEEE 802.11p and C-V2X technologies, and so must be discussed within the industry. The 5GAA ‘safe harbour’ proposal that 10MHz channels in the 5.9GHz band should be reserved for each technology will facilitate this equitable use.

## C.4 Costs

*What is needed to add C-V2X (e.g. radio front-end, processing back-end, security, etc.)?*

New chipsets and other associated physical layer elements will be needed to support C-V2X. Antennas will need to be upgraded/replaced to receive and transmit over the 5.9GHz band. Some automotive OEMs believe multiple antennas are needed for V2V, to ensure 360-degree coverage. However, much of the processing capability required for C-V2X has already been established for Uu connectivity, although the addition of V2V communications across the PC5 interface will require additional changes to the telematics systems, along with relevant internal mechanisms to control the car (e.g. automated actuation/braking).

*Where are messages to be analysed and warnings generated – in the telematic control unit (TCU) or in another electronic control unit (ECU)?*

The processing location of warnings and messages will be heavily dependent on the V2V use cases deployed, and will depend on the architecture within different vehicles. Messages and warnings could be processed within TCUs or within separate ECUs.

*Will this make the TCU a safety-critical part? If so, what is the impact on cost?*

Some automotive OEMs commented that the TCU or other control unit is not expected to become safety critical, because no vehicle will ever be dependent on connectivity features alone. Others took a different view, stating that the TCU would become a safety-critical component. The cost impact will vary depending on what is currently supported in different vehicles.

*Are there any requirements for an updated antenna to support C-V2X?*

Upgrade or replacement of existing antennas is needed to support transmission in the 5.9GHz band. Antennas must also support the spectrum used by MNOs. Many automotive OEMs considered that C-V2X is likely to be cheaper to implement than IEEE 802.11p (and would also be cheaper than a combination of IEEE 802.11p for V2V, plus cellular for V2N). This was partly because an integrated PC5/Uu chipset solution is expected, but also because higher penetration is expected, with greater economies of scale as penetration increases. Integrated chipsets are not expected for DSRC/ITS-G5 technologies with cellular, and these solutions will continue to require dual-chipsets and antenna systems to be installed in vehicles. One vendor commented on the potential installation of both C-V2X and DSRC/ITS-G5 technologies in a vehicle, which would require an additional antenna plus filters to distinguish communications and to avoid interference.

*How much will security infrastructure cost and who will pay (e.g. digital certificates, blacklists)?*

The cost of a centralised security infrastructure (e.g. to store security information for multiple car types) could be significant, but it was unclear how this would be funded. Some suggested that the EU, national governments or the insurance industry might fund security infrastructure, because of the key safety benefits of the technology. Several MNOs thought the costs of the security infrastructure for V2V will ultimately be borne by the customer – through road tax, licence-plate charges or increased vehicle prices. Others considered that the cost of security infrastructure will be ‘low to moderate’ and should be shared among the MNOs, infrastructure operators and the automotive OEMs.

*What is the cost impact of C-V2X on chipset/modem/TCU?*

The cost impact of C-V2X stems from chipset costs, antennas and other associated radio and control elements. One participant commented that C-V2X has been developed on top of existing cellular research and development efforts and infrastructure (which DSRC/ITS-G5 has not) and so will be cheaper in the long run.

## C.5 Benefits

*What output in terms of impact/benefit can we expect from the ongoing trials?*

The functionality of C-V2X in real-world road situations will be demonstrated through trials. Most agreed that C-V2X will outperform IEEE 802.11p. Many view the key benefit of C-V2X as being its future evolution path (guaranteed backward compatibility), which should facilitate a smoother and more cost-effective evolution to 5G.

Future large-scale trials in China are expected to demonstrate the safety, security and social benefits of C-V2X. MNOs expect that the trials will also demonstrate how Uu connectivity and the PC5 interface can provide richer services when functioning together. Others commented that the main benefit will be to demonstrate how C-V2X can support new business models and promote the technology within the industry and ecosystem.

*What are the key performance targets for C-V2X (reliability, latency, range, bandwidth attenuation, processing, interference, etc.)?*

Targets for C-V2X have been set in comparison to IEEE 802.11p – overall, C-V2X will outperform IEEE 802.11p in practice. One vendor added that simulations suggest that C-V2X will have a range 20–30% greater than that of IEEE 802.11p technologies.

*Which 3GPP releases (e.g. Release 14) are these targets aligned with?*

Performance targets are aligned with 3GPP Release 14, as described in 3GPP specification 22.806.