Cost Analysis of V2I Deployment

Final Report

Report for 5GAA

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1 Executive Summary

This is the final report of a study carried out by Ricardo, with support from our partner Roke, on behalf of the 5G Automotive Association. The purpose of the study has been to analyse different Vehicle-to-Infrastructure (V2I) deployment options from a financial, business and market point of view, while avoiding going into the technical discussion of the superiority of one technology over the other. Therefore, the objective of this report is to improve the understanding of the costs and their variability, as well as the challenges and opportunities around the four deployment options, to inform the development of business cases. The focus is on the EU and US markets and four deployment options were considered, which comprise of a combination of direct and mobile network communications technologies. Mobile network communications with the vehicle supported by the cellular network (Uu) is considered as part of the V2I system in each option, while three of the options also include direct communications (802.11p and PC5) that uses dedicated spectrum.

Option A – Pure cellular network-based (Uu) system

Option B – Combined system of Uu and an 802.11p-enabled RSU

Option C – Combined system of Uu and a PC5-enabled RSU (i.e. C-V2X solution)

Option D – Combined system of Uu and a dual radio RSU with both 802.11p and PC5

Research and development activities related to connected vehicle applications have been ongoing for over two decades, and there is now movement towards wider scale deployment of communication technologies in both vehicles and road infrastructure. However, deployment activities have been fragmented and relatively slow due to continued emphasis on research, no common vision of communication technologies and market uncertainty, making it challenging for most stakeholders to develop suitable business cases. A lack of widespread and aligned commitment by vehicle manufacturers, which in part has been caused by unclear regulatory positions, has negatively impacted other drivers and overall confidence in the wider market.

In this study, we have performed an extensive literature review and engaged with 25 key stakeholders to gather both primary and secondary evidence on the financial, business and market factors that impact V2I deployment. A cost analysis has also been carried out to provide quantitative outputs that supplement the narrative and support conclusions and recommendations.

The study recognises that direct and mobile network communications technologies have distinct advantages and disadvantages, in terms of their technical performance and costs – and so it is difficult to make direct comparisons. As the decision to deploy either technology by road operators will depend on the commitments by OEMs and regulatory positions, as well as the specific deployment scenario, there are a range of deployment activities seen across EU and US. Some road operators are focusing on roadside unit (RSU) deployments and others on mobile network communications, while many are adopting hybrid approaches.

The selection of communication technology originates from the V2I use cases and services that the road operators want to provide to the road users. These vary substantially between different regions and road operators. They range from traffic information services to safety services. Road operators perform a cost benefit analysis that compares the costs of a given solution, including communication technology options, with the anticipated benefits and potential risks or limitations. Then, based on this analysis and other criteria, such as available funding and potential partners, decide on the most suitable deployment option for them. Therefore, there is no complete consensus among stakeholders on the suitability of different communications technologies to support all V2I use cases.

The outputs of the cost analysis show that a pure cellular deployment approach in Europe and US is 40-45% lower cost compared with the deployment options that include RSUs, although the exact costs are heavily dependent on the specifics of the deployment sites and access to existing backhaul. Feedback from four road operators indicates that some road operators are starting with a pure cellular deployment approach utilising the developed cellular networks to communicate with vehicles and access quick and low-cost benefits from V2I services. Despite some recognised V2I performance challenges for cellular (Section 4.2), the current performance of the cellular network in terms of latency, reliability and coverage is deemed sufficient for their needs. Depending on the road type (i.e. V2I activity), cellular network data costs for V2I vary between 3% - 65% of the total in-year cost for pure cellular deployment (Figure 7-3). It is not completely clear who will cover the data costs and under what business models, but it is likely to be one or more of the vehicle owner, the vehicle OEM, the service provider or the road operator.

There are also real-world examples of cellular networks supporting low latency (<100ms) use cases but this may not be replicable under all conditions and in all locations. Therefore, it is acknowledged that smart use and positioning of fixed or mobile RSUs would play a complementary role for the successful local implementation of V2I services or use cases i.e. at places where it is particularly needed along the road network or at intersections for road safety or traffic efficiency reasons. Improvements with the introduction of 5G and associated approaches may enable more use cases to be delivered via the cellular network alone, but exact improvements in capability and the costs associated with this, are currently unknown. It is also not clear to what extent these costs would be passed on by MNOs to end users. When comparing costs between different options, there must also be recognition that the higher costs incurred in options with RSUs (Options B, C and D) may realise greater benefits. Furthermore, variation in aspects such as backhaul and cellular network availability make it very challenging to apply a common cost or technology approach across different deployment activities.

There are also examples of deployment activities where RSU are being deployed at specific sites and for targeted use cases, where the RSU is collocated with existing infrastructure and the delivery of use-cases in that location may be better suited to direct communications, allowing those benefits to be realised and justifying the additional costs. In these situations the use of RSUs is seen as a way of guaranteeing performance of certain use cases or services by those road operators (typically safety-focused use cases with very low latency requirements of around 100ms), enabling them to deliver a broader range of use cases in certain locations than would have not been possible with a cellular only approach for communicating with the vehicle. Costs of RSUs can be reduced by carefully selecting sites that require the least additional investment (e.g. existing roadside infrastructure with sufficient existing wired backhaul), and considering synergies with small cell deployment by MNOs, particularly in urban environments. Viable business cases for densification are primarily relevant to urban areas and so a proportion of urban installations are assumed to be suitable for joint deployment.

Based on the cost analysis, stakeholder feedback and research carried out as part of this study, it is clear that a mix of technology approaches exists, reflecting the different needs and priorities, starting points and approaches of different road operators, and other V2I stakeholders, as well as local availability of vehicles that can benefit from the V2I infrastructure. An approach to deploying V2I systems that use cellular network-based technologies augmented by direct communication RSUs in selected locations, will lead to a cost effective V2I system that is able to support the complete spectrum of V2I use cases and the largest user base. Supporting interoperability and data sharing in the backend, will bring the greatest value and benefit to all stakeholders.

The study also demonstrates that RSU deployment of V2I at large scale can result in significant costs, between EUR5 billion - EUR8 billion in the EU and between USD7 billion - USD12 billion in the US. Achieving this scale of deployment and investment will require cooperation. In particular, there is the potential for cities, road operators and MNOs to capitalise on synergies in motivations and activities around joint small cell deployment. This could result in V2I cost savings for urban road operators of around EUR275 million and USD375 million in EU and the US respectively, by 2035. Additional cost savings would be available to the stakeholders responsible for the deployment of small cells.

2 Introduction

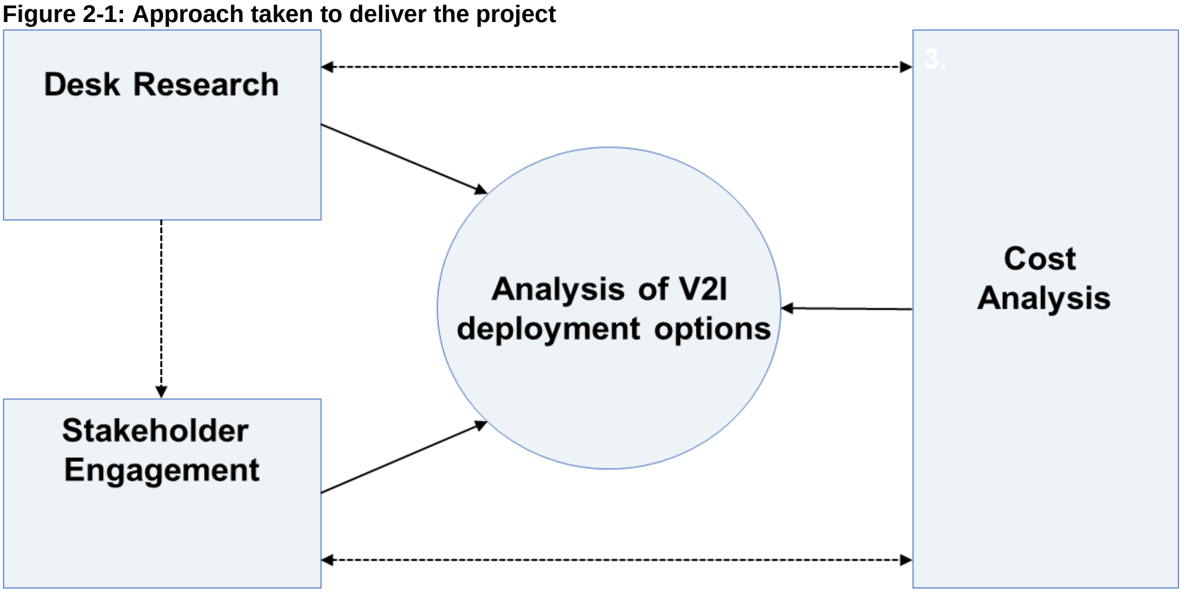
Cooperative ITS (C-ITS), known as ITS in the US, are revolutionising the car industry and will improve mobility systems as a whole. Through vehicle-to-anything (V2X) communications, vehicles can exchange data directly with other vehicles (V2V), directly with the road-side infrastructure (V2I) and even directly with pedestrians (V2P). Communications using the cellular network are vehicle-to-network (V2N) and may include Vehicle to Network to Vehicle (V2N2V), Vehicle to Network to Infrastructure (V2N2I) and Vehicle to Network to Pedestrian (V2N2P) communications.

V2X is an essential starting point for the development of autonomous vehicles [1]. Better road safety is typically the main aim of V2X, but the scope extends to include efficient transport services and smart city use cases. Significant R&D efforts have been made over the last two decades on V2X, and activities are now starting to transition towards larger scale deployment. There is huge potential in the benefits that nationwide V2X services can bring, and there are tangible opportunities for both the private and public sector to play key roles. However, the scale, speed and viability of roll out is being challenged by uncertainty across the regulatory, technology and market landscapes.

With a focus on V2I and V2N2I communication rather than V2V/V2N2V, this report provides an analysis of the costs associated with different infrastructure deployment options, which include both direct and mobile network communication technologies. The study has been conducted from a financial, economic and market perspective, while considering the challenges and opportunities, and complementary nature, associated with each of the communication solutions. The scope of this covers the US and EU, and so the respective regulatory landscapes have been considered accordingly. The overall purpose of the report is to serve as a non-technical guidance document for V2I key stakeholders on the most beneficial deployment options in terms of cost, as well as discussing the business opportunities presented by each of the solutions and potential opportunities for collaboration with other stakeholders. The report is based on comprehensive desk-based research, stakeholder engagement with industry representatives and cost analysis modelling. Across four main stakeholder groups (Road Operators, Mobile Network Operators, Automotive OEMs and Technology Suppliers), a total of 25 stakeholders were engaged with. Further details on these stakeholders can be found in Annex 1. The approach adopted in this study is outlined in Figure 2-1.

This is the final report of the study carried out by Ricardo, with support from our partner Roke, on behalf of the 5G Automotive Association.

Figure 2-1: Approach taken to deliver the project



2.1 Definitions

3GPP: The 3rd Generation Partnership Project (3GPP) is the global collaboration of telecommunications standards bodies, responsible for developing technical specifications for cellular technologies.

802.11p: The current IEEE standard that defines the Wi-Fi based communication in vehicular environments. The technology forms the lower layers of Dedicated Short-Range Communication (DSRC) systems - Wireless Access in Vehicular Environments (WAVE) in the US, and ITS-G5 in Europe.

C-ITS: Cooperative Intelligent Transport Systems (**C-ITS**) refers to transport systems, where the cooperation between two or more ITS sub-systems (personal, vehicle, roadside and central) enables and provides an ITS service that offers better quality and an enhanced service level, compared to the same ITS service provided by only one of the ITS sub-systems.

C-V2X: V2X delivered through communications made via **Uu** connectivity or the **PC5** interface, both of which are part of the technical specifications developed by 3GPP.

PC5: Part of the 3GPP standardised **C-V2X** solution, **PC5** is a direct-mode communication technology operating in the globally harmonized ITS band (e.g. 5.9 GHz).

Uu: A network communications interface between user equipment and a base station for an LTE (4G) or NR (5G) 3GPP cellular system operating over mobile network operator licensed spectrum. **Uu** can be used for backhaul and/or long range communication between the infrastructure and vehicle.

Roadside Infrastructure (RSI): Installed equipment within the road system that can actively generate or convey information relevant to V2X services and provide a suitable location to co-locate an **RSU**.

Roadside Unit (RSU): A communications unit that supports direct V2X communications and can incorporate a **Uu** interface for backhaul and/or long-range communication with the vehicle. **RSUs** are typically connected to a central system through backhaul (via fibre, copper, or **Uu**) but can also be stand alone, and are often integrated into existing **roadside infrastructure**.

Service: **V2I** services or applications are a clustering of use-cases based on a common denominator, while the use case outlines the function of the system.

Small Cell: A **small cell** is a miniature cellular base station. They complement the macro cellular network to improve coverage, add targeted capacity, and support new services and user experiences.

V2I (Vehicle-to-Infrastructure): Communication between a vehicle and infrastructure in the road system (e.g. traffic lights, cameras, and signage). The communications can be using a direct communications technology, or indirect via a cellular network, which is also known as Vehicle-to-Network-to-Infrastructure (V2N2I & I2N2V).

This list is non-exhaustive and serves as an introductory guide to some of the more frequently used terms in this document. A glossary is available at the end of the report.

2.2 Current V2I landscape

From an infrastructure perspective, the C-Roads Platform[1] is the main C-ITS deployment activity in Europe with a current focus on ITS-G5 for direct communications and Uu for long-range communications with the vehicle, although since 2016-2017 some deployment activities have started to include C-V2X (e.g. ConVeX consortium, Concorda, etc.). The next phase of C-Roads (from 2020) aims to move away from piloting and into wider scale deployment[2], as well as additional focus on urban deployment and public transport. It should be noted that for short range (direct) communication, the ITS-G5 access layer can be replaced with 3GPP PC5 access layer without affecting the long range communication on Uu and backend communication, since the payload is the message as specified by ETSI.

The RSU deployment landscape is similar in the US, where the preferred technology until recently has been 802.11p-based and activities are still mainly focused on R&D and early pilot deployments, with some steps being taken towards larger-scale deployment. Federal funding through the US Department of Transport (USDOT) supports many projects, but State-level DOTs are increasingly involved in coordinating and financing deployment activities. Similar to the EU, different operators are selecting different solutions, with support for network-based connected vehicle applications seen most clearly at the City and County level.

From a vehicle perspective, uptake of direct communications technologies has been slow, although recent market commitments from two large OEMs (VW and Ford) could be an indication that broader fleet penetration of these communication capabilities is one step closer, in part motivated by V2V use cases. Furthermore, adoption may also be influenced by the efforts ongoing in regional New Vehicle Acceptance Programs (NCAP) that are highlighting the safety benefits of V2X direct communications. Vehicle OEMs (e.g. Volvo, Daimler & BMW) have also deployed network supported V2X services and general cellular connectivity of vehicles is expected to increase significantly in the next 5 years. Technology chipset suppliers are also combining direct and mobile network communications into a single platform, with PC5 and Uu available in a single-chipset given the overall complementary nature of the technologies.

The relatively slow and fragmented uptake of V2I services by OEMs and Road Operators (ROs), is largely attributed to the general uncertainty and cost to governments for infrastructure deployments. After years of testing, both the EU and US were moving forward with 802.11p for direct communications to support V2X. However, the more recent introduction of C-V2X as an alternative direct communications option has altered the picture and, in both regions, regulatory support for 802.11p technologies (ITS-G5 and DSRC) has taken a step back. In Europe, a proposed C-ITS Delegated Act supporting ITS-G5 was not approved by 21 Member States in June 2019, partly over concerns to a perceived lack of technology neutrality. In the US, no action has been taken on a 2016 proposal to mandate DSRC in all new vehicles, and the Federal Communications Commission (FCC) have plans to allocate the upper 20MHz of the 5.9GHz spectrum for sole C-V2X use, while reserving a further 10MHz for ITS use (C-V2X or DSRC). This NPRM (notice of proposed rulemaking) also proposes that 45MHz of the 75MHz in 5.9GHz band previously reserved for ITS applications, should be opened for unlicensed use, leaving only 30MHz for exclusive ITS use.

2.3 Key stakeholders in V2I deployment

The stakeholder ecosystem of V2X is complex and will vary between deployment sites. In the case of V2I, there is always a user of the service, as well as a RO and a vehicle OEM who are responsible for the infrastructure and vehicle side, respectively. In addition, mobile network operators (MNO) are responsible for any related data traffic going through their cellular network, while across the technology

[1] Joint initiative of European Member States and road operators for testing and implementing C-ITS services.
[2] For example, Austria plan to deploy 500 ITS-G5 units. [30]

value chain, there are a number of suppliers and technology companies responsible for making available the hardware and software that supports V2I solutions. Finally, there are research and academic organisations involved[3], as well as service providers who can be separate actors to the RO, OEM, or MNO.

Box 1. Example of stakeholders involved in V2I deployment

NordicWay – Sweden

NordicWay is a collaboration between public and private partners in Finland, Norway, Sweden and Denmark. In the Swedish pilot, the following organisations are involved:

- The **Swedish Transport Administration** is responsible for connecting the traffic management centre database to the V2I ecosystem.
- **Ericsson** is responsible for the development and operation of the Swedish Traffic Cloud and Interchange Server.
- **Kapsch** provided hybrid 802.11p and cellular RSUs and **Volvo** and **Scania** equipped vehicles with on-board units that support communication.
- **Springworks** (technology provider) have implemented their user interface in vehicles to provide the service to the end user.

The figure below summarises these stakeholders, providing a generalised description of their role. A more in-depth analysis of stakeholder motivations and the implications for deployment is provided in Section 5.1.

Figure 2-2. Involvement of key stakeholders in V2I deployment

Deployment Stakeholder	Involvement in V2I
Road Operators	Responsible for making road data available through deployment and operation of infrastructure supporting V2I services along the road network. Usually these are public bodies although some private road networks are operated by private or quasi-private companies.
Mobile Network Operators	Traditionally, the MNO has provided connectivity through the cellular network or fixed line infrastructure. They have evolved to work directly with vehicle manufacturers to supply cellular connectivity to vehicles, and increasingly they are working with road operators and cities to offer traffic management and smart city services.
Suppliers / Technology Providers	Businesses that work across the V2X value chain supporting the supply of hardware and software to OEMs, MNOs and ROs. Production of the final RSU often includes several actors in the supply chain – e.g. chipset manufacturers supplying to module makers who then supply to RSU vendors. Finally, a system integrator is required to connect physical infrastructure to the central ICT system.
Vehicle OEMs	Not directly involved with road infrastructure deployment, but integral to an effective V2I solution through equipping vehicles with direct and mobile network communications technologies and making vehicle data available. Likewise, OEMs rely on the existence of infrastructure to deliver V2I services, which can be seen as a product differentiator for vehicle sales and

[3] Especially in trial and pilot deployments

		safety performance and delivers value to automakers before V2V communications can be pervasive.
	Service Provider	Responsible for creating the service solution by establishing the interface between the end-user and the other stakeholders. They are integral to business operations as they sell the service to end user, RO and OEMs. Service providers operate by collating traffic, technology and usage data to deliver a service to users or distribute to other stakeholders.
	User of the Service Solution	A key stakeholder in any service dominant. In V2I, the user could be an individual driver, a fleet operator or the road operator themselves.
	Academic / research	Although not a significant player in wide-scale deployment, they are fundamental to technological development and testing of communications solutions. In many cases they collaborate with public road operators to create, operate and co-finance V2X testbeds.

3 V2I Deployment Options

V2I communications involves communication between vehicles and the road system. Within the road system, there are many types of equipment that generate data (i.e. sensors, cameras, weather stations). When this data is collected and analysed, it can be used to provide real time information to drivers, benefitting road safety and traffic efficiency. This information may be presented directly to drivers inside the vehicle or through infrastructure that conveys information, such as traffic signals and variable message signs.

3.1 Overview

This report considers three distinct technologies: cellular network-based communications which can be 2G, 3G, 4G and/or 5G, and two direct communications that use dedicated spectrum - 802.11p and PC5. Based around these technologies, four deployment Options (Box 2) are considered in this study and are the subject of the cost analysis that is presented in Sections 6 and 7. Option A is presented in more detail in Section 3.2 while Options B, C and D are presented together in Section 3.3.

Box 2. Four infrastructure deployment options considered in the study

Option A – Pure Uu-based system

Option B – Combined system of Uu and 802.11p-enabled RSUs

Option C – Combined system of Uu and PC5-enabled RSUs (i.e. C-V2X solution)

Option D – Combined system of Uu and dual radio RSUs with both 802.11p and PC5

Note: Uu in the options refers to mobile network communications with the vehicle, although RSUs and RSI may also incorporate a Uu interface for backhaul.

The first deployment option involves using only the cellular network (i.e. Uu interface) for communications with the vehicle, in other words relying exclusively on Vehicle-to-Network-to-Infrastructure (V2N2I) connectivity, whereas the remaining options also support direct communication between the vehicle and the infrastructure. Unlike direct communications that use dedicated spectrum, cellular communication uses the commercially licenced network. While there may be some performance differences between 802.11p- (Option B) and PC5-based solutions (Option C), the system components and costs are assumed to be very similar. The general view among stakeholders and costs identified in the study, was that there is no tangible cost difference from an infrastructure deployment perspective[4], although one stakeholder did note that it is possible to achieve further cost optimisation with chipset solutions that integrate Uu with PC5 (C-V2X). Each option incorporates mobile network communications between the vehicle and infrastructure, and so from a high-level component and cost perspective, Options B, C and D represent Option A plus an RSU unit. Having cellular communication capabilities integrated into the RSU unit represents an idealised scenario from a redundancy and connectivity perspective[5], but the backhaul capability may not be used if wired backhaul is available. Two RSU vendors indicated that around half of their units are sold with Uu, while another vendor said their share of units with Uu was less than 10%. An overview of the options is presented in Figure 3-1 to indicate the high-level differences between them.

[4] C-V2X is expected to be cheaper at the vehicle level [35].

[5] The Uu interface can be used for backhauling and vehicle communication (eNB-type RSU). The Uu interface can be used as the primary or backup backhaul option for information exchange with backend systems and for security certificate exchange with the PKI.

Figure 3-1. Overview of the four infrastructure deployment options

	Option A	**Option B**	**Option C**	**Option D**
	Pure Uu-based solution	***Combined system of Uu and 802.11p-enabled RSUs***	***Combined system of Uu and PC5-enabled RSUs (i.e. C-V2X solution)***	***Combined system of Uu and dual radio RSUs with both 802.11p and PC5***
Data exchange between road system[6] and vehicle	LTE/5G Uu	DSRC/ITS-G5 (RSU) and LTE/5G Uu	PC5 (RSU) and LTE/5G Uu	PC5 and DSRC/ITS-G5 (RSU) and LTE/5G Uu
Backhaul	Network equipment: Fibre	RSU: Uu or Fibre/ethernet Network equipment: Fibre	RSU: Uu or Fibre/ethernet Network equipment: Fibre	RSU: Uu or Fibre/ethernet Network equipment: Fibre
Operations	Network equipment: MNO	RSU: RO Network equipment: MNO	RSU: RO Network equipment: MNO	RSU: RO Network equipment: MNO
Components[7]	Roadside Infrastructure (RSI) Cellular Network Central ICT System	Roadside Infrastructure (RSI) Cellular Network Central ICT System RSU	Roadside Infrastructure (RSI) Cellular Network Central ICT System RSU	Roadside Infrastructure (RSI) Cellular Network Central ICT System RSU

[6] Typically, the road operator, road traffic authority, or via a third-party service provider.
[7] In addition to equipped vehicles

3.1.1 Complementary technologies

Direct and mobile network communications technologies have distinct advantages and disadvantages, in terms of their technical performance and costs. The decision to deploy either will ultimately depend on use cases selected, regulatory conditions, vehicle manufacturer commitments, as well the specific deployment environment. The limitations and challenges for each solution can be addressed within a system that considers both. Systems that do not incorporate both can still be effective, but may be limited in the services that can be deployed.

Considering the value of direct communications technologies for local relay of Cooperative Awareness Messages (CAMs) with stringent requirements, and mobile network communications to deliver longer-range broadcast messages – there is clear complementarity between the two solutions. This is evidenced by the deployment activities across the EU and US today, which often take a hybrid approach incorporating both communication solutions. While Uu operates in the traditional mobile broadband spectrum, direct communications technology operates in the ITS 5.9GHz band and although it is developed on different standards it can be co-located with Uu for backhaul and interoperability can be enabled in backend-systems. Similar to 802.11p, PC5 operates in the ITS 5.9GHz band where transmission is independent of the cellular network. It displays a higher level of complementarity with Uu as both are integrated communication modes of C-V2X under the 3GPP technical specifications and related standards. Furthermore, there is a defined intention to incorporate PC5 in smartphones and a forward compatible evolution path to 5G C-V2X with new capabilities to support C-V2X for autonomous driving. The two direct communications radios are not compatible with each other and so vehicles and infrastructure using the different solutions will be unable to communicate with each other directly [1]. However, it is possible to have combined systems that include C-V2X and 802.11p that can communicate with the respective in-vehicle systems thanks to common application layers.

Both, direct and mobile network communications technologies have evolutionary pathways, with Uu and PC5 pathways to 5G New Radio (NR) integrated under 3GPP standards, and 802.11p evolution to 802.11bd governed by IEEE. This highlights the work that is ongoing across all communication technologies to improve the operational performance and expand the number of use cases. In each case, important questions around liability or enabling business models remain to be fully answered.

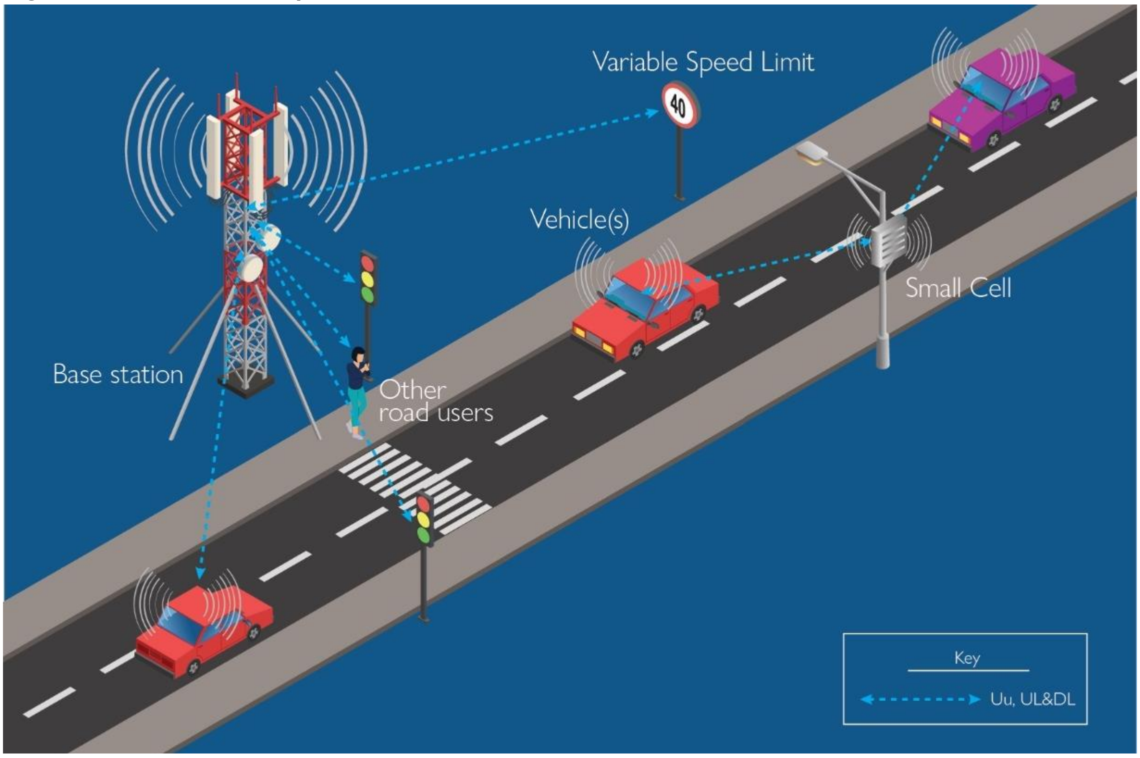
3.2 Pure Uu implementation (Option A)

Deployment Option A relies on communications through the cellular network (Uu) via the commercial licensed spectrum to transmit messages between the vehicle and the road system. This option can therefore be more accurately described as V2N2I (also I2N2V). While direct communications (802.11p & PC5) have a short-range, this option enables longer-range communication. As shown in Figure 3-2, the Uu interface is used to transmit data between a connected device and the mobile network, via cellular equipment such as base stations. Transmission of data from device to base station is called uplink, while communication from base station to device is called downlink[8]. While the figure shows how Uu can be used by RSI (e.g. traffic light) for backhaul purposes, the infrastructure can also use wired backhaul to connect to central backend systems.

The figure also illustrates how small cells could be used to increase network capacity as part of MNO network planning. A promising opportunity is to jointly deploy small cells with V2I deployments (see Section 5.3.2). Information supporting V2I services can be delivered to drivers in the vehicle on embedded displays, or through aftermarket devices such as smartphones and personal navigation devices. Some OEMs provide these applications and third party technology providers are also involved in application development, often funded by the public sector.

[8] Messages in the downlink (DL) can be unicast, broadcast or multicast.

Figure 3-2: Overview of a pure-Uu based solution



In addition to the parts of the ecosystem presented in the figure above, central backend systems that collect, store and process data, and applications that deliver the services to the end user are also required. Additional information on the architecture is provided in Annex 3.

3.2.1 Cost considerations

The existing cellular network, available services and scalability mean that a range of services (see Section 4) can be delivered to many road users and reach very high road coverage without the need to deploy additional infrastructure units. Significant investment has already been made in mobile network equipment and roll-out of 5G has started in both the EU and US. These activities would occur regardless of V2X and so costs for infrastructure deployment that are incurred by MNOs are not considered within the scope of this study, as they are not expected to be specifically covered by V2I stakeholders. Existing cellular networks are also well covered with authentication and encryption, so no significant additional costs for security are needed for this solution. Large scale deployments in Finland and the Netherlands have followed this approach.

An important consideration for both road infrastructure and vehicle owners is the reliance on cellular data and who will pay for it. An actively subscribed SIM card, either embedded in the vehicle or in the driver's smartphone, will be needed to engage with services. Additional data usage and cost could be accepted by drivers if the service improves the driving experience, shown by the success of WAZE and Google Maps applications. However, it is more difficult to assess whether drivers and/or OEMs would be willing to incur additional costs associated with safety services. Depending on the V2I deployment ecosystem, third party service providers may be involved in hosting backend systems that ensure continuity of the applications in roaming scenarios. The costs associated with this service are not considered within the scope of the study, because there does not yet appear to be clarity on either the magnitude of this cost or how it would be allocated.

An important component in Option A is the RSI, which may actively generate or convey information relevant to V2X services. Two common cost components that can be incurred are backhaul installation and upgrade of the hardware that generates and transmits relevant information. Evidence from stakeholder engagement and literature [2] [3] highlights that these costs are not always incurred, but they can be significant when they are necessary (see Section 6.1.1). For example, if the RSI does not have backhaul, or the legacy equipment is old and needs upgrading. Backhaul from roadside infrastructure increasingly uses cellular connections, which can offer reduced costs and complexity than creating new wired links. It should also be noted that often these upgrade activities are planned or ongoing as part of general infrastructure and ITS maintenance activities and so the costs are not necessarily always counted within specific budgets for V2I. Further information on costs is detailed in Section 6.

3.2.2 Key benefits and challenges of a pure cellular approach

The key strength of mobile network communication (Uu) for V2I relates to the existence of an already established communication network (to which more than 180 million vehicles on the roads are connected using mobile networks in 2020 [4]), and the improvements expected from the introduction of 5G and other cellular developments. Consequently, there are more existing cellular applications that can support V2N2I services, compared with direct communication technologies. These factors result in a relatively lower cost route to delivering V2I services (compared with RSUs), although there are limitations in the ability of Uu to support the most safety critical use-cases and areas of poor network availability or no coverage exist. The quality of service available through LTE mobile networks is generally considered suitable to deliver the majority of V2I informational services, although stakeholders voiced concerns over latency and reliability of today's Uu network to deliver certain advanced services (see Section 4) and most stakeholders recognise there is a need for RSUs in certain 'hot-spot' locations. Improvements with the introduction of NR and associated approaches such as predictive quality of service and network slicing could address these concerns going forward (see Annex 3) but are not available today as standard MNO products. This may enable more use cases to be delivered via the network, but the costs associated with this are currently unknown and it is not clear to what extent these would be passed on by MNOs to end users.

A principle challenge associated with a pure-Uu approach is the gaps in network coverage for rural areas in large countries and unknown costs related to continuity of the applications in roaming scenarios. This is relevant for both EU and the US but the concern was expressed more strongly by US stakeholders. Areas where there is poor network coverage can also be places where safety related V2I services are especially valuable, such as on mountainous or remote roads. While MNOs continue to invest significantly in networks, the public sector may be needed to support network deployments in areas where there is not a viable business model for the MNO. Alternatively, these areas may represent locations where RSUs could be deployed to provide communication coverage, although consideration still needs to be given to installation costs and viable business models.

As discussed above, a key question for cellular is who will cover the data costs and what are the business models. A few years of data subscription may be included in the car price, but at some stage the driver may need to decide whether to continue to pay for the service. MNOs are adapting their business models to offer lifetime SIM contracts for ROs and OEMs, but lifetime connectivity in vehicles for V2I applications is still far from guaranteed. Furthermore, stakeholders have highlighted that if networks start handling more safety critical data traffic, then business models should be adopted that give the industry a benefit / incentive. For example, if a certain Quality of Service (QoS) was agreed contractually, then road operators may have to pay higher fees to MNOs for this guarantee. ROs may be able to bear a share of the costs, particularly where a Uu approach to communicating with vehicle avoids RSU deployment and the high costs associated with installing and maintaining RSUs.

3.2.3 Technology evolution and developments of cellular technology

The continuous evolution of cellular technologies is coordinated by 3GPP, and new standards and approaches will improve the ability of cellular to deliver current and future V2I services. Engagement with ROs suggests that they are aware of the potential that 5G brings and that market developments are being closely followed, particularly regarding the role that 5G will play in progress towards automation. However, 5G and related technologies will still need to be tested and demonstrated for V2I services and acceptable business models will need to be set up. For current use cases, some stakeholders noted that 4G is sufficient and so the real potential of 5G could lie in enabling future use cases by addressing the currently perceived limitations of 4G. Demonstrations have also shown that by using network optimization techniques it is possible to obtain very low latency values over LTE, allowing operators to satisfy, over existing networks, use cases that require near-immediate response times [5].

On the network side, MNOs are also aware of the potential for 5G and Multi-Access Edge Computing (MEC) to provide guarantee of QoS, but there is a question about the best use of the network and meeting business needs, and adding this capability can increase costs to the MNO. One MNO noted that if safety is critical and the network is supporting significant traffic related to V2I, then public–private partnerships (PPP) should be considered to give the industry a benefit. Furthermore, if a certain QoS was guaranteed and liability implied, then road operators may have to pay higher fees to MNOs for this guarantee. A potential challenge that may emerge and will need addressing is ensuring uniformity of experiences on reliability and latency for critical use cases across multiple MNOs covering the same region. Additional information on NR and MEC is provided in Annex 3.

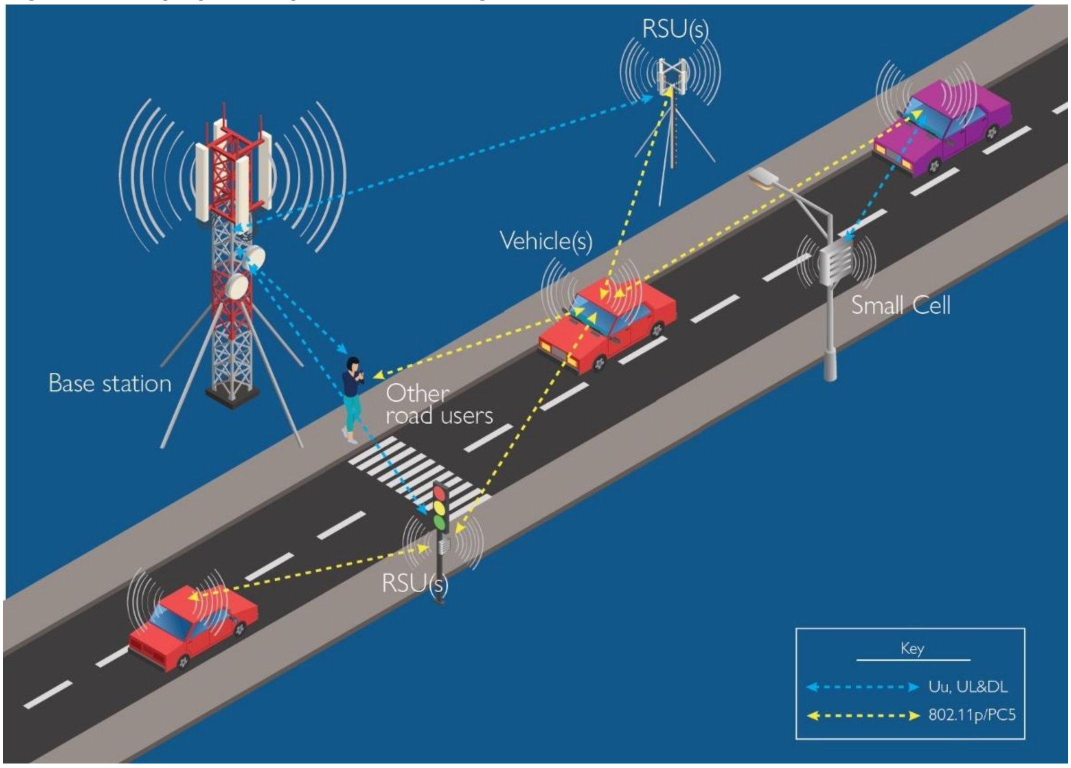
3.3 Deployment options with direct communication technologies (Options B, C and D)

While there may be some differences from a technical point of view between 802.11p- and PC5-based communications, functionally and from a component perspective Options B, C and D are similar. Therefore, these options have been presented together in this section:

- **Option B – Combined system of Uu and 802.11p-enabled RSUs**
- **Option C – Combined system of Uu and PC5-enabled RSUs (i.e. C-V2X solution)**
- **Option D – Combined system of Uu and dual radio RSUs with both 802.11p and PC5**

These options involve the deployment of dedicated communication RSUs that support direct communication between the vehicle and RSU, independent of a cellular network connection or mobile subscription. The RSUs may have a Uu interface to provide a secondary communication channel with the vehicle and/or to support backhaul. These options assume a combination of direct and mobile network communications functionality that could be used to support different use cases (see Section 4). The ecosystem is identical to Option A, apart from the addition of an RSU that is connected to the central ICT system, either through wired backhaul or using the cellular network (Uu) for wireless backhaul. The RSUs are typically integrated with fixed existing roadside infrastructure (e.g. traffic signals) but can also be deployed independently and on mobile units. Stakeholders are also investigating the potential to jointly deploy small cells with RSUs, either alongside or in the same physical unit (see Section 5.3.2).

Figure 3-3. Deployment options combining direct radio and indirect cellular communications



3.3.1 Cost considerations

Additional costs are incurred to deploy the RSUs and maintain them. Cost data from previous studies and input from stakeholders as a part of this study have confirmed that the hardware costs for RSUs are typically a fraction of the total lifetime costs – with a significant proportion taken up by backhaul, installation and operation. Backhaul and installation costs will vary significantly between sites but can usually be reduced when the RSU is collocated with existing roadside infrastructure that provides an installation site and access to power and backhaul. Further information on costs are in Section 6.

3.3.2 Key benefits and challenges of RSU deployments

A key strength of direct communications technologies is the thorough testing and standardisation activities that have taken place across the EU and US, specifically with V2X use cases. This provides confidence to deployment stakeholders in the ability of direct communications to support V2I priority use cases with the most stringent requirements and is a factor behind the continued interest from road operators in deploying RSUs. An additional strength of direct communications is the lack of ongoing cellular data costs incurred, with stakeholders commenting that some ROs place importance on the ability to control total costs closely with RSU deployment.

While the 802.11p technology has undergone more testing than PC5-enabled RSUs (as standardisation efforts started in 2004), PC5 has been shown to have some technical (i.e. link margin, range) and potential economic advantages (large ecosystem driving economies of scale) [6]. In addition, PC5 can leverage with minor adaptations most of the applications and upper layer standards (including ETSI-ITS, ISO, SAE/IEEE) already built and refined for the 802.11p access layer by the automotive industry and others in the ITS community for over a decade [7]. Both solutions have commercial availability, which recently includes combined 802.11p and PC5 chipsets. For fractionally higher CAPEX and OPEX costs, dual-technology chipsets could offer a solution to technology fragmentation that future-proofs infrastructure investment, at least during the current period of uncertainty.

A challenge with RSU-enabled V2I systems is that the service can only be delivered to vehicles equipped with the corresponding communication technology. The current lack of equipped vehicles on the road up to now has been a significant barrier for ROs looking to transition to wide-scale deployment. Even now with some OEMs committing to significant deployment (e.g. Ford and VW), given the lifetime of vehicles, the penetration of equipped vehicles into a country or region's vehicle fleet is expected to be gradual over the next 10 to 15 years, thus limiting the benefits that can be achieved in the early stages of deployment. Furthermore, feedback from smartphone industry stakeholders as part of another 5GAA study concludes it is unlikely that 802.11p communication technologies will be integrated in smartphones, although an intention to incorporate PC5 in smartphones has been defined. [8]

To date, regulatory uncertainty (see Section 2.2) with regards to a potential technology mandate and availability of spectrum has not helped in the development of a common vision across stakeholders, which could have contributed to the slow take up on both the vehicle and infrastructure side. In respect to the FCC NPRM, Virginia DOT have temporarily stopped deployment of DSRC RSUs in their testbed, while another RO commented that a continuation of the current uncertainty over direct communications could slow deployment of infrastructure. Some stakeholders have also expressed the concern that reducing the amount of spectrum available for ITS applications (and in particular the spectrum available to DSRC to a single 10 MHz channel) may lead to a degradation of performance especially in areas of high traffic congestion, which could potentially impact safety. These uncertainties are passed on as challenges for suppliers, and while dual mode RSUs have been made available, stakeholder engagement in this study indicated that there does not yet seem to be significant interest from ROs or OEMs. In any case, ROs are likely to accommodate whatever decision is made by OEMs to ensure that the maximum number of vehicles are supported and looking forward, there is promise that an outcome of the FCC NPRM and the neutral stance on spectrum in Europe may form a more stable situation from which deployment can scale.

The costs associated with RSU deployment is seen as a challenge, with several stakeholders voicing their concerns about the potentially high maintenance costs for RSUs. The Dutch Ministry commented specifically on the high labour costs that can be incurred, noting that personnel costs are approximately EUR1,000 per intersection for repair, in addition to any wider societal costs associated with closing a road while maintenance occurs. However, an important takeaway is that remote monitoring can be used to avoid on-site maintenance and therefore labour costs. Operating RSUs in a testbed environment has meant that some operators have been able to utilise in-house technicians, although for larger scale deployments it is recognised that dedicated maintenance teams would be required to meet uptime requirements. There may be opportunities for partnerships between ROs and MNOs to address the challenge of maintaining a network of connected RSUs, discussed further in Section 5.3.2.

3.3.3 Technology evolution of direct communication technologies

3GPP is a consortium of seven national or regional Standards Development Organisations (SDOs) that develops technical specifications for cellular systems, which are transposed into global standards. New features and services are introduced into the standards through an incremental process, with new functionalities or enhancements to the existing ones added in each release of the specifications, in a backward and forward compatible manner. Initial C-V2X V2I services are expected to be provided over LTE PC5 (Release 14), as both RSU and OBU products are already available in the marketplace. Release 16 will add the option of the NR PC5[9], and experience tells that the lead time from completion of the specifications to product availability could be two years. NR V2X devices will include LTE-V2X functionality allowing them to communicate with other LTE-V2X devices (vehicles and RSUs). V2X will continue to benefit from advanced roadmap planning from 3GPP and over time, new advanced use cases may emerge through NR V2X and future updates, which may result in mid-life upgrades of RSU technology, which is common practice today with wireless infrastructure.

802.11 technology is also evolving. The IEEE is working on 802.11bd [9], an evolution of 802.11p which proposes higher throughput, higher reliability (by reducing packet collisions) and improved range compared to 802.11p. 802.11bd is designed to be backward compatible with 802.11p, whereby at least

[9] Initial specification of the NR sidelink was only agreed in December 2019.

one mode of 802.11bd must be interoperable with 802.11p. The standardisation is planned to be completed by December 2021.

4 V2I Services

V2X contains a growing number of services at varying levels of maturity that move beyond existing ITS, such as road tolling, to achieve enhanced road safety, improved traffic efficiency and reduced environmental impacts. The scope of this report includes currently standardised services that involve communications between the vehicle and infrastructure (V2I), either directly or via the network.

A key finding from this study is that the ability of a communication technology to deliver V2I services is not always clear cut. There are thresholds and ranges to the requirements for the various service use-cases, while the performance of a given communication technology also has ranges and variability. Ultimately, a decision by a RO to support a use-case (or bundle of use-cases) with a particular technology will be made on a case by case basis, accounting for technical requirements, cost-benefit analyses and risk mitigation. Further discussion on the suitability of communication technologies to deliver use cases is presented in Section 4.2.

A set of common V2I services and example use cases are presented in the table below. This includes those that have been defined as priority services by the EU C-ITS platform, identified by 3GPP, as well as services that appear frequently in deployment activities across the EU and US, and as specified by ETSI and SAE respectively. The range of services being considered for deployment is generally comparable between EU and US [10], although in the US there is more of a focus on SPaT/MAP services at intersections. The USDOT, ITS JPO website provides an overview of all connected vehicle applications that they sponsor [11] while the C-Roads Platform provide up to date documentation of common C-ITS Service Definitions [12].

Table 4-1. Common V2I services and example use cases (non-exhaustive)

Service	Use cases
Hazardous Locations Notification	Weather conditions
	Emergency vehicle approaching
	Queue Warning / Traffic Jam Ahead
	Curve Speed Warning
Road works warning	Lane closure
	Road operator vehicle approaching
In-Vehicle Signage	In-vehicle speed limits
	In-vehicle signage
	Shockwave Damping[10]
Signalized Intersections	Signal violation / Intersection Safety
	Traffic signal priority request by designated vehicles
	Green Light Optimal Speed Advisory (GLOSA)
Mobility Services	Information on fuelling & re-charging
	On and off-street parking information and[11]
	Park & Ride information
	Traffic information & Smart routing
Probe vehicle data	
Vulnerable road user protection	

[10] Also "local hazard warning" in ETSI Categories
[11] Also known as "Automated Parking System" in 3rd Generation Partnership Project (3GPP) releases

There are also driver services that are provided by third parties independent from road operators and OEMs, which are mainly applications similar to those in the 'Mobility Services' category in the table above. These are mainly delivered to the driver via smartphones and can be enhanced when enriched with data from the road system and vehicles (e.g. routing and map applications). Enhanced V2X (eV2X) use cases that introduce automated driving and cooperative manoeuvring have been defined by 3GPP as part of Release 16, which have more stringent requirements not supported by LTE (See Annex 4) but are not considered in the scope of this study.

4.1 Selection of V2I services

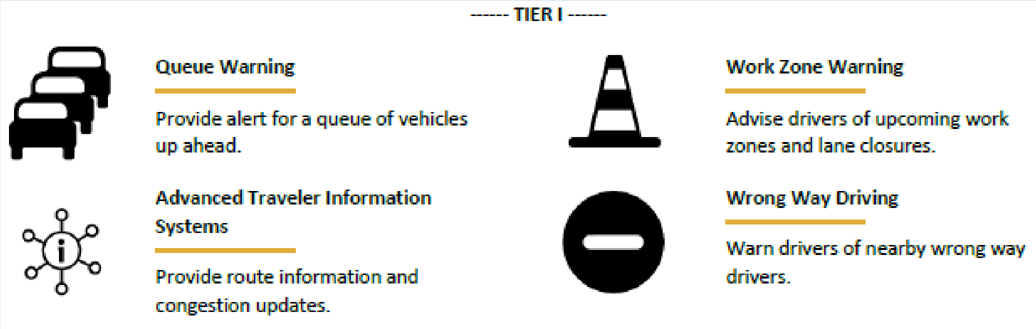
Generally, interest from deployment activities can be seen across all services presented in the table above. This is to be expected considering that the most progress has been made in testing and standardising these services. Evidence from online resources and engagement with stakeholders involved in deployment, shows that road operators are typically most interested in deploying the safety services related to hazardous location notification and signage. Separate analysis carried out by Ricardo in 2019 identified 'Road Works Warning' as the most common service across 18 national C-Roads projects that were assessed. This finding is also in line with outputs from stakeholder engagement carried out as part of this study. Other popular services include weather conditions, in-vehicle signage and speed limits, probe vehicle data and traffic jam ahead. As hotspots for accidents and congestion, services delivered at signalised intersections are also very popular, although they tend to be more challenging to deliver, due to lower delay tolerance and more complex delivery that often requires communications to and from the vehicle. Ultimately, the selection of services to implement will be based on assessment of potential impact and will still include services that are less well defined. For example, vulnerable road user protection was frequently highlighted by road operators as a priority service but with recognition that more work is needed to test and standardise this service.

It is important to highlight that services of interest to ROs will differ between regions, depending on factors like climate, local policy mandate and existing infrastructure/ITS technology. For example, a cost-benefit analysis as part of NordicWay revealed that 'slippery road' and 'weather conditions' are the most beneficial services to provide in Finland – due to their subarctic climate.

V2I services will also differ between urban and non-urban environments. In non-urban areas, less priority is usually given to services delivered at intersections, as there are fewer of them. In contrast, intersection services are usually more popular in urban deployments where large buildings can block visibility and impact intersection safety, and priority for designated vehicles (e.g. public transport, emergency vehicles, trucks) can be effective in congested areas. Furthermore, along highway environments, applications that target the safety and efficiency of freight vehicles are often popular. In Texas, growth-induced congestion is getting worse each year and freight traffic is now a big issue. This has provided the impetus for a four-year connected freight corridor project, covering over 870 miles. Consideration of different deployment environments also highlights the variation in stakeholders, which will influence the choice of services. Mobility stakeholders other than the road operator may include public transport operators, emergency services and freight companies. In such deployment scenarios, services will be selected that benefit all parties involved, as clearly demonstrated in the Texas example (see Box 3).

Box 3. Including both private and public sector in selection of services

Texas Connected Freight Corridor. The project carried out an outreach activity with public and private sector partners to identify 12 shortlisted applications. These were split into three tiers of priority based on a ranking exercise. Tier I services are shown below:



4.2 Suitability of communication technologies to deliver V2I services

While some road operators may select use cases based on those that can be provided with the technology available, in most cases deployment activities identify priority use cases first (as discussed above) and then select the communication solution that would deliver those use cases in the most cost-efficient way. Evaluation of direct and mobile network communications solutions will consider the costs and potential benefits, but a decision on whether the communication solution can deliver the required level of service defined by standards or demanded by the implementing stakeholder(s), is a fundamental aspect that will influence the choice.

Two basic performance parameters are typically considered:

1. **Allowed delay of message delivery (latency)**
2. **Reliability and guarantee for data exchange.**

Other requirements that are evaluated include the ability to support high mobility performance, communication range, frequency of messages, data protection and security.

Total system latency for V2I, as defined by ETSI TS 101 539-3, corresponds to the difference between the time at which the data is available at data source (e.g. traffic light) and the time at which the warning is presented on the vehicle display or time at which a direct action is requested to the vehicle electronic system, if applicable. This includes both the latency in the originating ITS-S (i.e. traffic controller), the wireless network and the receiving ITS-S (i.e. vehicle). Reliability of the system is typically expressed as a percentile (i.e. 95%) and considers confidence level of meeting the system minimum performance requirements every time.

For primary or critical road safety use-cases that reduce the risk of collisions – including Signal Violation and Intersection Safety, ETSI TS 101 539 estimates that a 300ms end to end latency time is required to avoid false decisions based on old data. In terms of the speed of data transmission, sources generally agree that the maximum latency must not exceed 100ms [13] [14], and it can be even lower for some use-cases [13]. This predominantly applies to intersection safety services where delays or incorrect information passed to the driver can result in a collision. In ETSI V2X application requirement specifications, the level of priority (i.e. level of communication performance necessary) assigned to communications are based on the criticality level of the traffic safety situation that the V2I service is being delivered in. More specifically, the level of priority is linked to the Time-To-Collision (TTC). The highest level of priority (Level 0), is assigned to a pre-crash situation. The next level of priority is assigned to a warning situation (driving assistance or automatic action), while the lowest level of priority is assigned to a driver awareness situation, involving road hazard signalling (RHS). Services delivering information to the driver, have the highest delay tolerance.

An overall assessment of whether direct or mobile network communications are suitable to support use cases will depend on the specific conditions, such as the level of congestion (data traffic) or network availability. In general, the performance of DSRC and PC5 direct communications are sufficient to support all of the V2I services in Table 4-1 under all circumstances, although some information services will be better suited to longer range communications (i.e. distributing information to drivers on a road hazard 2km ahead). Supporting these information services can be achieved comfortably using todays cellular networks, and they may also be able to support the safety critical services under certain conditions. While the latency of LTE-4G is often adequate (50-150ms), reliability of the service performance cannot be guaranteed and is 'best effort'. As a result, in many V2I deployments, the most safety critical services are only delivered using direct communications. There are examples of these services being delivered over Uu and one stakeholder commented on the benefits of mobile network communications for intersection services. For example, in the 'traffic signal priority' use case, mobile network communications can provide the traffic light control application with earlier warning about an approaching priority vehicle, allowing the intersection to be managed more pro-actively. It is also worth noting that the higher bandwidth and the lower latency of 5G (frequency range 1) may enable existing services that cannot currently always be supported by LTE. 5G and network optimization techniques are discussed in Annex 3.

Overall, this study has not identified a consensus among stakeholders on the suitability of different communications technologies in supporting 'safety critical services', and it is generally accepted that for now there is no aligned view on this. However, it is clear that there are synergies between direct and mobile network communications technologies that can enhance range of services and geographic coverage of a V2I system. Evidence from deployment activities reviewed and feedback from the majority of road operator stakeholders (11) in this study suggest that ROs are aware of this synergy.

5 Financing Deployment and Business Models

The public sector (e.g. road operator or a transport authority) is typically the main stakeholder involved in V2I infrastructure deployment, both from the perspective of being the infrastructure owner/operator (IOO) and considering that the priority services being deployed have large societal benefits e.g. increased road safety, environmental thanks to improved traffic efficiency. To date, support for deployment activities has mostly been through public research and innovation funds, which to begin with allowed the new V2I technologies and services to be developed and tested. However, the shift towards wider scale regular public funding for V2I infrastructure deployment has been slow and challenging; CAPEX/OPEX costs for RSUs are traditionally high, and new and evolving technologies have contributed to uncertainty in the market – hindering deployment in vehicles and a common vision between stakeholders and regions.

It has been suggested that public funding alone will not be able to realise the full benefits of V2X, and deployment of V2I infrastructure will likely require financing sources from different private sector industries as well as the public sector [15]. Effective cooperation between stakeholders will be vital in developing viable business models that can meet both the cost and benefit requirements.

This section discusses some of the practical considerations around supporting deployment of V2I, looking at stakeholder motivations and business models, considering how activities are currently funded, and thinking about how this may evolve in the future.

5.1 Business models and understanding motivations

An important action is to identify suitable business models that work for all. A definition that works well in the context of C-ITS is:

> *"A Business Model describes the way in which organizations produce and deliver value to their customers/consumers"* [15]

This captures the importance of 'value delivered' by organisations, which is directly linked to the motivation of stakeholders. For example, the public sector is motivated by delivering societal benefits – where the value of their actions may be improved road safety or traffic efficiency. Private organisations take a business point of view and are primarily motivated by increasing sales of products or services, which can be achieved through delivering value to customers (B2B or B2C) that may be a differentiator in the market. In the specific context of deploying V2I, motivations that can be attributed to the main stakeholder groups are summarised in Figure 5-1. below.

Figure 5-1. V2I deployment motivations of the main stakeholder groups[12]

Stakeholder	V2I deployment motivations
Road Operators	The main deployment motivation is safety of road users and road workers. Improved accessibility/mobility and environmental benefits are also important motivations. Road operators will usually have a mandate to meet certain KPIs within a fixed / limited budget. Where the road operator is a private or quasi-private organisation, safety will still be a key motivation but improvements on road efficiency will become more important.
Vehicle OEMs	Increasing the sales of vehicles is the primary motivation of OEMs and offering V2X services can be an effective brand differentiator, in terms of safety or services. While typically not directly involved in roadside infrastructure deployment, ability to provide V2I services will depend on the availability of appropriate V2I infrastructure. For example, Ford have actively been pursuing partnerships with road operators to encourage this deployment, while Audi's Traffic Light Information service is available in 25 US cities through 11,700 connected intersections.
Mobile Network Operators	Network operators can increase profits though V2I from increased data traffic through the network and the expansion of revenue streams across the spectrum. They will often have fixed line business and software business streams across backend systems in V2X ecosystem. In line with the transition to an internet-of-things offering and 5G, MNOs are investigating new service offerings for smart cities that could include V2I data. MNOs may also be interested in densification of cellular infrastructure, possibly through incorporating small cells with V2I deployment.
Suppliers / Tech Providers	Organisations in this stakeholder group are motivated by sales of products and services across the V2I value chain, such as chipsets, and RSU/OBU modules. They are therefore sensitive to activities of OEMs and ROs, who usually represent the final customer.
Service Provider	Service providers generate value from sales of services directly to the driver, or to the RO/OEM. They may also be able to monetise data in other ways

[12] Other stakeholders that can be involved in V2I, include real estate and data harvesting companies.

beyond V2I. The service provider can be any of the above stakeholders, or a separate third party.

In addition to these primary high-level motivations that have been identified, other more future thinking and strategic motivations were voiced across the stakeholder groups, which are important to recognise.

- OEMs and MNOs are particularly interested in the longer-term development of automation in the transport sector, which will revolutionise the vehicle market and result in significant growth in data volumes. Involvement in V2X is an important opportunity to prepare mobile networks and vehicles, and influence decision making for longer term development.
- More generally, early involvement in deployment activities is needed for improved learning and understanding of V2I services, allowing stakeholders to maximise delivery of value to customers and consumers.

5.1.1 The importance of cooperation and public-private partnerships

As already highlighted, with road safety and traffic management efficiency improvements being central benefits of V2I services, the public sector will remain a core stakeholder. The C-ITS Platform likened deployment activities as an 'orchestration of services', with the role of 'orchestra conductor' indisputably remaining under the public's authority umbrella [16]. However, truly functioning public-private partnerships and cooperation need to be established if there is to be large scale deployment that overcomes deployment fragmentation [17]. The Connected Vehicle Pooled Fund in the US notes the potential for V2X to support a fundamental advance in surface transportation, but recognises that;

> *'in order to realize this potential, a connected vehicles system and environment will require unprecedented collaboration between the private and public sectors, on a scale not required in the current loosely coupled system'* [18].

These partnerships could extend to co-investment, but at a minimum, cooperation is required to develop a common vision between stakeholders, facilitate effective exchange of data and provide certainty of delivering value from use cases. For example, the ability to deploy some use-cases such as traffic signal priority or stationary vehicle warning is dependent on a chain of actors that must work together, taking a pragmatic approach towards the use of data and responsibility of costs. Across Europe and the US, there are many examples of important activities that are looking to support this level of cooperation between stakeholders in the field of V2X.

Table 5-1. Non-exhaustive table of relevant activities supporting cooperation in V2I deployment

Region	Activity
EU	Amsterdam Group, CAR 2 CAR Communication Consortium, C-ITS Deployment Group, C-Roads Platform, The Data Task Force, ERTICO
Global	5GAA,
US	Connected Vehicle Pooled Fund Study, Cooperative Automated Transportation (CAT) Coalition[13], Crash Avoidance Metrics Partners LLC (CAMP), ITS4US

5.1.2 Cooperation and business model challenges

Examples such as FirstNet in the US, which brought together a purpose-built public safety network with AT&T, prove the value and possibility of effective PPPs, but there are barriers to overcome. Beyond stakeholder motivations, in practice many factors will influence a decision to invest time and money in

[13] Includes AASHTO, ITS America and ITE. Includes working groups, which were formerly a part of the Connected and Automated Vehicle Executive Leadership Team (CAV ELT) and the Vehicle-to-Infrastructure Deployment Coalition (V2I DC).

supporting deployment activities, including return on investment (ROI), profitability, and market conditions. Some specific challenges for V2I business models have been highlighted below. A discussion on supporting cooperation can be found in Section 5.1.3, while analysis on approaches to support accelerated V2I deployment is presented in Section 5.3.

Uncertainty | A challenge for V2I, particularly in the private sector, is the current uncertainty at a technology, policy and organisation level [17]. This uncertainty heightens the risk of making an investment but not having a market sufficiently ready to generate the desired value. For private sector, the risk is that the pay back is not quick enough, while for the public sector the risk is that the benefits take too long to materialise or not at all due to technological / behavioural challenges.

Confidence in deployment at scale | Significant efforts have been made in both EU and US that clearly demonstrate the impact of V2I to deliver important safety, efficiency and environmental benefits. The potential impact of these services have also been proven in pilot scale projects and testbeds, however, there needs to be confidence in the real-world, scalability of these benefits, which has been challenged by the uncertainty highlighted above. Stimulating investment has also proved challenging because benefits materialise over time, and a large part will go to users/society while road operators will have to bear upfront costs. RSI upgrade costs will be incurred in the case of pure Uu deployment (Option A), while more considerable investment will be needed where RSUs are also deployed. These concerns could begin to ease as regional efforts on NCAP emerge, thus creating more motivation for automakers to adopt direct communications and create a larger user base that RSUs would support.

Developing trust in variable and numerous deployment events | Developing and agreeing cooperation and business models on V2I deployment is not a single event, but an activity that must be engaged with, negotiated and talked over thousands of times across the EU and US. Of course, larger organisations will overlap across numerous activities, but the combination of stakeholders and local context will be unique for each deployment activity. This creates a challenge in overcoming the barrier of 'trust', which must be developed between stakeholders. It also creates a challenge for stakeholders who will need to identify the respective roles that should be considered, or recognise what roles are potentially missing to offer the proposed service solution. Given the range of objectives (motivations) identified above, it may become challenging to guarantee that respective goals are fulfilled [19]. Important efforts are being made to homogenise deployment, through resources such as the US ARC-IT and the C-Roads EU standards and profiles. However, the scale and variability in activities means there is no single route to cooperation or a common approach to selecting use-cases and communication technologies. The deployment of V2X infrastructure will not homogenise deployment arrangements and we will continue to see a range of deployment and operation set ups [20].

5.1.3 Supporting cooperation and business models

Two key concepts that are important in promoting V2I deployment and supporting business models, is interoperability and the availability of data. Achieving harmonised services using systems that are interoperable does not necessarily mean that deployments use the same communication technologies or involve the same stakeholders, but users must receive their services at the expected quality across Europe and the US, even when the underlying technology is different [21]. If this is achieved, it will address many of the challenges around deployment. A selection of relevant activities is listed below:

- In 2019, the C-ITS Platform released the latest specification for interoperability of backend hybrid (ITS-G5 & Uu), which describes the functionality and profiles that are necessary to provide hybrid communication via interconnection of backend systems. A Basic Interface (BI) is specified, independent of any deployment model chosen by a country/region or C-ITS actors, which allows information sharing [22].
- Multi-vendor interoperability for C-V2X based on both the ETSI and IEEE/SAE standards has been tested [23]. Interoperability between 3GPP and non-3GPP V2X technologies at the

application level has also been considered by 3GPP and ETSI[14], from a recognition that "*realizing the full extent of benefits from cooperative driving depends on the availability of a critical mass of capable and compatible vehicles on the road*" and that "*the long product lifecycle in the automotive market (i.e., 10 – 14 years)*" [24].

- The C-MobILE project is deploying C-ITS services in eight European cities using a common, interoperable architecture. The project is also identifying business models of service delivery concepts and stakeholder partnerships to create sustainable operations.
- In the US, the Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT) is an interactive, flexible tool to develop tailored regional and project architectures to meet local needs while supporting interoperability across key system boundaries [25]. ARC-IT is destined for the ITS National Architecture, to which regional architectures must conform required to receive funding from the Federal-Aid Highway Program.

In addition, interoperability of backend systems will be facilitated by architectures and agreements that support the sharing of data, bringing together data generators and service providers. Backend systems should aim to be similar between deployments, and solutions need to facilitate data sharing between clouds of different stakeholders. The Data Task Force, Data Access and Exchanges program, and Extended Vehicle standard are promising activities in regard to data sharing (Box 4).

Box 4. Making data available

C-roads, EU: WG2, Task force 4 have specified profiles to use standard Internet technology for information sharing of ITS information via backend systems in a scalable way. The standardized Advanced Message Queue Protocol (AMQP) provides publish/subscribe methods which facilitates a separation between backend actors. This solution is currently used in a trial solution to interconnect actors in Sweden, Finland, Norway, Denmark[15]. Other European countries are building systems according to the C-roads profiles[16]. Note, the solution is not bound to Europe, nor to ITS-G5 since the transport layer is payload agnostic

The Data Task Force, EU: This has been set up to take the first steps towards data sharing for Safety-Related Traffic Information in the European Union. It recognises the current barriers to data sharing and a proposes a cooperation model focused on reciprocity – OEMs can make vehicle data available to 3rd parties and in return they receive data from local authorities. If there is no reciprocity, OEMs can request reimbursement of costs for collecting and sharing the data. This is a good example of collaboration between two key stakeholders sharing data using a decentralised data collaboration architecture.

ITS Data Access and Exchanges program, US ITS JPO: Part of the ITS JPO Strategic Plan 2020–2025, this goal focuses on enabling access to core transportation data across the ITS ecosystem. Planned activities include enabling data access across jurisdictional boundaries in a trusted and efficient manner and providing guidelines and demonstrated examples for resolving key institutional adoption barriers such as privacy and cybersecurity [25].

Extended Vehicle standard, ISO 20077: Based on the 'extended vehicle' concept that promotes safe and secure access to vehicle data via an off-board facility, this standard defines the means of off-board data access and its interfaces, ensuring interoperability. The vehicle manufacturer is the data handler and provides third parties with access to vehicle data in accordance with technical, data protection and competition rules, through interfaces and means of off-board data storage.

5.2 Existing deployment activities

To date, deployment of V2I services has mostly been research and pilot based that is supported by fixed price funding from the public sector's infrastructure, road safety and innovation funds. In the EU,

[14] See ETSI TR 103 576-2. Available here: https://www.etsi.org/deliver/etsi_tr/103500_103599/10357602/01.01.01_60/tr_10357602v010101p.pdf
[15] NordicWay - https://www.nordicway.net
[16] Harmonised C-ITS specifications"- https://www.c-roads.eu/platform/documents.html

central European funds such as TEN-T, CEF, Interreg and structural funds have been used to support most projects. In addition, some regional and local funds have also been mobilised. In the US, the most reliable sources of funding have come from the federal level, specifically the ITS JPO discretionary funds. Local investment at the state level has also been made and there are examples of initiatives aimed at helping local level investment, including the CAT Coalition [26] and Connected Vehicle Pooled Fund Study [27]. Examples of private sector investment are largely focused around testbed and proof of concept activities. Private sector involvement in RSU deployments has usually been as a deployment partner to test technologies and further their understanding (see Box 5).

Box 5. Example of industry partnerships in a deployment project

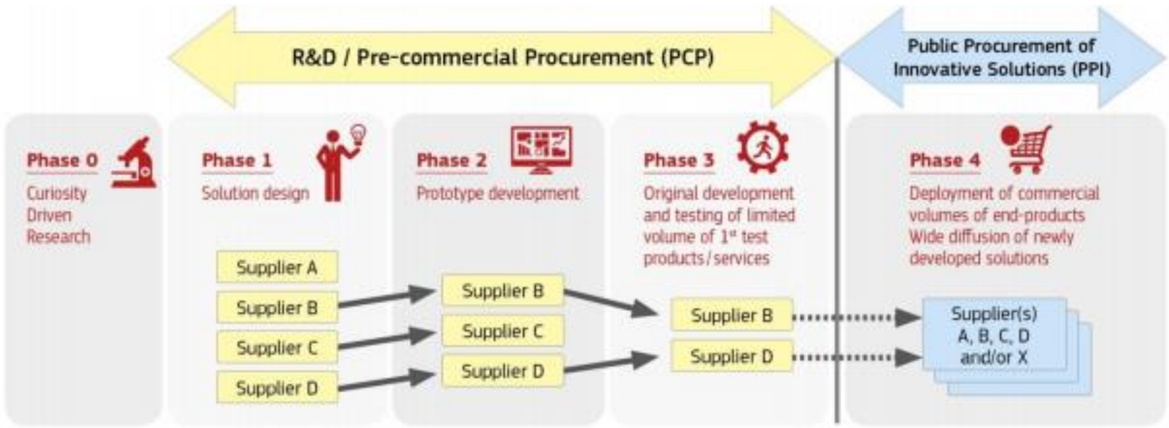
'**Connected freight corridor', Texas**

- The Texas Connected Freight Corridors (TCFC) project received a FHWA grant in 2017 to deploy RSUs and connected vehicles to showcase up to 12 V2V and V2I applications focused on freight safety and mobility.
- The project has 8 freight industry partners who will have an opportunity to gain valuable safety, mobility, and environmental insights.

The challenges discussed in Section 5.1.2 explain why public sector funding and supporting financial instruments will be needed to help bridge the gap between pre-commercial R&D deployment and conventional public procurement, even after a technology has been proven and is available on the market. In Europe, P4ITS was a European coordination and networking project with an objective to support Public Procurement of Innovation (PPI) for Cooperative ITS (C-ITS). In 2016, they reported that there was movement beyond pre-commercial procurement and into deployment in volume and they supported PPI as an important bridging funding mechanism for this transition (Figure 5-2.) [21].

> *"PPI is when contracting authorities, possibly in cooperation with additional private buyers, act as lead customer (also called early adopter or launching customer) by procuring 'innovative' solutions (not the R&D to develop them) that are newly arriving on the market but that are not yet available on large scale commercial basis due to a lack of market commitment to deploy."*

Figure 5-2. Innovation procurement



There are examples from the EU, US and other regions, of V2I services deployed in large scale projects that have effectively leveraged involvement and funding from multiple stakeholders across the public and private sector. However, at the moment these appear to be mainly limited to cellular deployment options, such as in the 'Virtual RSU' in Australia, the EU-funded NordicWay and Talking Traffic program in the Netherlands (see Box 6). Each of these examples have adopted general architectures that ensure the interoperability of C-ITS services across different V2X application servers [28]. Furthermore, the NordicWay and Talking Traffic example both use smartphone applications, developed within the project or already available on the market, as a route to delivering the service in the vehicle. This ability to deliver services through cellular applications on smartphones and PNDs in vehicles is an important factor that supports the 'quick win' attitude that some stakeholders are adopting. In contrast, direct communications technologies cannot be as easily retrofitted in the vehicle and are most likely to arrive through new vehicles. The Dutch Ministry anticipates in the future an even stronger rate of development in the cellular track but noted that while the choice between current deployment technologies is uncertain, the Ministry wants to deploy available and scalable solutions as fast as possible to meet the societal challenges they have to face today and tomorrow, and not just over the next 10 years.

Box 6. Example of joint public-private funding in a deployment project

'Talking Traffic', The Netherlands

- The partnership is a collaboration between the Dutch Ministry of Infrastructure and Water Management, 60 regional and local authorities and national and international private companies.
- A European procurement scheme called an "Innovation Partnership" was used to realise a co-funding collaboration model (55% public and 45% private) through which a total of 90 million euro was invested for the period 2016-2020. A public/private governance body was also established within the project.
- Each private stakeholder remains the owner of its components and services in the overall Talking Traffic ecosystem, while the public funding was a co-investment by the public authorities in the development and exploitation of each of those components/services without any transfer of IPR to the government.

There are also examples of wider scale deployments involving RSUs. One of the largest RSU deployment activities in the US in in Georgia, where a total of 1,700 DSRC and C-V2X RSUs are planned for deployment across Atlanta at critical signalized intersections. Supporting this activity has been the heavy investment in deploying 4G LTE routers at all non-connected traffic signals in the state of Georgia, meaning there are over 6,500 traffic signal online in the state [29]. The C-Roads Platform in Europe also has a vision for large scale deployment with transnational interoperability. Pilot activities are taking place in 18 Member States, although there is only evidence to date from Austria of wider scale deployment as they look to deploy up to 500 ITS-G5 units on Austria's highways by 2023 [30]. In Germany, most of the 49 RSUs will be dismantled at the end of the research activities of the German C-Roads project[17].

However, limited investment in large scale / nationwide deployment is being driven by uncertainty in vehicle OEM commitments, regulatory uncertainty and the high cost of RSU deployment. For the last decade, Michigan DOT have been in the V2X conversation and have been relatively proactive in deploying V2X. However, being at the leading edge of RSU deployment could leave them at risk of incurring costs to retrofit infrastructure as technology evolves. While some public sectors agencies may be able to justify a similar deployment approach – for others the high cost, combined with uncertainty is a combination that will prevent RSU investment.

While the Netherlands thus far haven chosen a cellular approach for their deployment projects as this makes the most sense in their specific conditions, they are following market developments and are open to direct communications technologies, as long as the benefit is clear. If V2V evolves such that vehicles are adopting this technology, then the Ministry will make sure to adapt the regulatory framework if needed to accommodate this. Virginia DOT also noted that future deployment considerations will be based on the opportunity to communicate with equipped vehicles. The connected freight corridor in Texas is another example of wider scale RSU deployment, but the ability to cover 870 miles on the relatively limited federal funding (USD6 million) will be achieved by adopting both direct and mobile network communications and is thanks to the significant investments that have already made in state-

[17] BMVI response to a parliamentary question in April 2020. http://dipbt.bundestag.de/doc/btd/19/188/1918806.pdf

wide communication architecture, fibre and backend software. Furthermore, the project does not yet know which direct communications will be deployed and a lot will depend on the FCC decision.

It is clear from the range of deployment activities highlighted above, that stakeholders are aligned in their vision for a safer, more efficient and more connected transport system. It is also clear that wider scale deployments are emerging from different technology starting points, depending on the bundles of services that stakeholders happen to be motivated by and the local context. Section 4 described how different use cases are more suited to either mobile network or direct communications and so an important takeaway is that regardless of a deployment starting point - there will often be additional benefits in working towards a comprehensive V2I system that uses complimentary direct and mobile network communications types, and supports interoperability and data sharing in the backend.BMVI

5.3 Accelerating V2I deployment

The actions taken by national and international bodies supporting C-ITS have been instrumental in the development of V2X technologies and will be vital in scaling deployment. For example, the role of Intelligent Transportation Systems Joint Program Office (ITS JPO) extends from identifying and assessing technologies, through to supporting implementation, scaling and maintaining ITS. Their Strategic Plan 2020–2025 includes actions to support accelerating deployment through several initiatives. These provide a useful summary of some of the key actions that are needed to reduce uncertainty for market investors and minimize industry risk.

- **Evaluation** – support evidence-based policy options and decisions.
- **Professional Capacity Building (PCB)** – support knowledge and technology transfer.
- **Architecture and Standards** – enable interoperable, secure, and efficient ITS safety and mobility services.
- **Communications** – knowledge-sharing opportunities and partnerships.

Overall, most parts of the V2X ecosystem are set up in both EU and US, but an element that is outstanding in both regions is a security certification management system, which is important for generating trust in the V2X systems and supporting interoperability. In both Europe and the US, progress is being made to develop these systems. The EU CCMS is in the process of being set up with a first Root Certificate Authority expected to be available for testing purposes from April 2020. C-Roads are engaged with the EU-CCMS and expect to operate within the trust model so that infrastructure can communicate with vehicles, supporting V2I services. In the US, the department of transport started development of on a proof-of-concept message security solution for V2V and V2I communication. According to stakeholders, the federal government have said they will document the potential approaches but have moved away from being a federal certificate authority and have decided to let the industry build the solution. Neither Virginia DOT nor Michigan DOT have implemented certification distribution for their deployed RSUs as they are waiting for a central solution. Michigan DOT are actively engaging with the industry to ensure investment will be in concordance with industry direction.

Reflecting on some of the successful wider scale deployment activities that exist, costs have been manageable, and benefits have been demonstrable. As we move into adoption at scale, fundamental relationships need to be identified that demonstrates the value to participating stakeholders and facilitate viable business models. The matrix below highlights where some of these important relationships may exist between stakeholders.

Figure 5-3. Analysis of motivations and connections between stakeholders in the context of V2I infrastructure deployment

Brings to	Road Operator	Mobile Network Operator	Supplier/Tech Company	OEM	Cooperation opportunities
Road Operator	Societal benefits: • Roads safety • Traffic efficiency • Environmental benefits	• Access to real estate and utilities • Market for cellular in V2I ecosystem	• Market for V2I technologies to be sold	• Enhanced value of connected vehicles through deployment of infrastructure • Road/traffic data	As owners of valuable road data and real estate, ROs can be in a strong position to cooperate with OEMs and MNOs.
Mobile Network Operator	• Cellular coverage and related cloud / data services • Experience with operation of network of equipment	• Expand spectrum revenue • Preparation for autonomous driving and 5G	• Increase market for V2I technology and improved delivery quality of cellular service	• Cellular coverage and related cloud / data services	As we move towards smart cities and societies focused on data exchange, MNOs can support road operators on connected infrastructure – joint deployment activities and operational support.
Supplier / Technology Provider[18]	• Supply and deployment of V2X infrastructure	• Supply and deployment of V2X infrastructure	• Increase sales • Extend V2X capability	• Supply and deployment of V2X infrastructure • Ensure that backend systems are compatible with OBUs	As providers of technology across the V2X value chain, there is the potential to work closely with customers to develop products and solutions that meet requirements.
OEM	• Value of connected infrastructure through deployment of connected vehicle & vehicle data	• Market for cellular services in vehicles	• Market for V2I technologies to be sold	• Brand differentiator • Preparation for autonomous driving	Coordination of connected vehicles and infrastructure is key to ensure benefits are achieved, particularly with the direct communications technologies.

[18] Covering Tier I-III and system integrators

Deployment motivations of road operators are most closely aligned with the value of V2I services and they are responsible for much of the infrastructure and data that can support V2I services. Therefore, they are best placed to instigate cooperation with other actors.

With respect to pure cellular solutions (Option A), road operators rely on the aggregation and distribution of road safety and traffic information to vehicles. The Virtual RSU, NordicWay and Talking Traffic projects demonstrate the importance of partnerships with network operators and technology companies who can manage the cellular communications and develop interoperable backend solutions and applications. The Finnish agencies have worked with MNOs in some of their pilot projects as they are the most likely stakeholder who can make business cases from these pilots. For cellular deployment, costs for road operators are comparably lower to RSU options, and benefits exist in the scalability of the solution. Furthermore, vehicles can more easily be retrofitted with applications to deliver the services through smart phones and PNDs. Therefore, while cooperation with OEMs is desirable, it is less important.

For RSU deployments, the infrastructure costs for road operators are higher and so there is conversely more emphasis on demonstrating the benefits. On a large scale, this can be difficult due to the uncertainty about the availability of compatible vehicles that will be on the road. In most cases, regulatory positions or OEM commitments have not been enough to generate the certainty required to commit large investment yet. However, there are local examples of cooperation between stakeholders that have been able to guarantee V2I service users. A good example is the Texas Connected Freight Corridor, that successfully partnered with eight freight companies, securing 1000 vehicles to communicate with and deliver value. Furthermore, an OEM referenced an example of effective cooperation with a national road authority to jointly install OBUs in some vehicles while they installed RSUs on mobile crash barrier vehicles to reduce risk of collisions. Coordination of OBU and RSU deployment is key to ensure benefits are achieved. Once the RSUs are in place, there are fewer barriers to extending the number or scope of V2I use cases if additional compatible vehicles start to use the roads. We may not ever see a common technology vision in vehicles, and penetration of technologies into the fleet is likely to be slow, and so localised RSU deployments that target specific use cases may continue to be a solution unless there are national efforts by governments, like C-V2X RSU deployment in China.

Another important takeaway from the matrix above is that each of the private sector stakeholders operate and are motivated by selling products and services. The size of the V2I market is ultimately defined by the number of compatible vehicles / devices and a demand for the V2I services, which must come from the vehicle owners. End-users of V2I use-cases are not interested in the technical characteristics of the system, but rather how the system can benefit them when used [31]. Across the smart mobility sector, there are examples of a general shift away from a goods-dominant perspective. For example, car sharing - where the customer is more interested in the value (e.g. convenience) rather than the physical good (e.g. buying a car). In order to support a movement beyond research and pilot based deployment, V2I activities may need to adopt a service-dominant perspective, to enhance the value of V2I technologies and establish a more sustainable V2I system [19]. Road operators should look to partner with these private organisations who have more experience in creating services from data and those private organisations that could benefit from this data. One mobile network operator commented that if a service is attractive for the end customers (i.e. driver), they might be more willing to transmit their data to the service provider in return for an improved service (e.g. Real Time Traffic Information with Google, HERE, TomTom etc.).

5.3.1 Multi-use

Another effective way to address the balance of costs and benefits and increase the viability of infrastructure deployment is to identify multiple uses for the same technologies or systems. While the services presented in Table 4-1 are a selection of the current priority for V2I deployment services, there are many other potential use cases and synergies for both industry and public agencies to deliver additional benefits and value from V2I activities.

Multi-use is particularly relevant for V2I deployment in city environments, where over the last few years we have seen a move towards smart cities and societies focused on data exchange (see Box 7). City authorities want to monitor the use of public space and performance of public operations, including waste, emergency services and climate measurements. There are also considerable opportunities across the transport, energy and industrial sectors for smart applications, including smart energy management, integrated public transport systems and logistics.

Scope for multi-use is also most clear in cellular systems, which are the backbone of an Internet of Things (IoT)-powered smart city. Developments in the cellular space, such as 5G and MEC, that enable multi-use effectively will accelerate the roll out of new use cases. Traficom commented that once a backend system has been developed that can facilitate data exchange between data sources and service providers, there is a huge amount of synergy and efficiency gains to be exploited. A key challenge for service providers will be the ability to trust information that is being shared and so approaches on security and audits will be important to enable multi-use.

Box 7. Multi-use in smart cities

Columbus, Ohio. US: The city of Columbus leveraged a USD40 million USDOT grant and USD10 million from Vulcan Inc. into USD500 million of funding for their Smart City vision. Activities will include data exchange, truck platooning, smart grids, smart streetlights, collision avoidance sensors, autonomous vehicles, and electric vehicle adoption. The high degree of public/private/academic participation helped Columbus in initially accessing the grant and stimulating further investment[19].

5.3.2 Joint deployment

One proposition that has real interest from MNOs and is being monitored by road operators is the joint deployment of cellular small cells with RSUs. This is mainly relevant in the urban domain where deployment of small cells can support the densification of the cellular network, which will be important for the MNOs to support the increased capacity needed to deliver the full benefits of 5G (especially mmWave), and accommodate a growing number of users and services relaying on data connectivity over the cellular network.

Deploying connected hardware can be a significant undertaking in terms of planning, access to utilities (power, backhaul) and maintenance. In rural areas, there can be specific challenges around the availability of power and backhaul, while deployment in urban and suburban areas are also challenging due to zoning and licensing restrictions. The planned increase in small cell sites, particularly in urban areas, means there is increased interest from MNOs to identify opportunities for collaboration that can save on costs and support the business case for installing new cellular sites, such as small cells. When looking at the deployment of RSUs and small cells, there are five types of synergy that could be exploited, summarised in Table 5-2 below.

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Table 5-2. The five levels of synergy that exist between RSU and SC deployment

1. Real estate	Access and licence to deploy on suitable street furniture
2. Power	Access to power for unit operation
3. Backhaul	Access to backhaul for connectivity with central systems (RSU) or core network (SC)
4. Components	Sharing of module or connectivity components
5. Installation and maintenance	Sharing of installation and maintenance efforts

These synergies can result in upfront cost savings for both the RSU (i.e. RO) and small cell owners (i.e. MNO). Where there is a need to incur costs related to power or backhaul, costs can be shared, and where there are not costs to share, the road operator can leverage access to the site and utilities in return for financial reimbursement or access to connectivity. Furthermore, service agreements can be made to allow joint maintenance that shares the operational costs. Leveraging expertise from the telco industry has so far not been something that many road operators or cities have done, and it is particularly relevant when considering joint deployment activities. Some MNOs have been investigating the maintenance of ITS infrastructure (including RSUs) since they have decades of experience in maintaining national networks of connected infrastructure. Cost sharing is explored in more detail in the cost analysis Sections 6 and 7. While the diagram above highlights deployment synergies, operational synergies may also exist whereby the infrastructure can be used to perform other useful functions for the RO.

Beyond synergies that exist between the stakeholders directly involved in V2I services, there may also be complementarity and potential for business models with other actors such as the power sector (see Box 8). Distribution network operators are also investing in cellular communications as they start to actively control their networks. For example, network monitoring will be needed to manage the integration of electric vehicles into low voltage networks with as little reinforcement as possible [32]. These activities consider many of the same functionality and cost aspects as in V2I deployments; communication technology, network cost, signal coverage and latency [33].

Box 8. Example of small cell joint deployment with power industry

In Japan, there is an example of MNOs and power companies co-investing in small cell deployment – with MNOs leveraging power line infrastructure in Japanese cities, which removes at least one of the barriers to dense urban roll-out – power supply. [34]

While the potential for multi-use of V2I infrastructure and joint deployment with cellular equipment such as small cells, there are several key challenges that need to be addressed:

- Street furniture is often something that is owned by the RO, but this is not always the case. For example, it may belong to a separate public agency or a transport operator – introducing an additional stakeholder.
- Service level agreements need to be confirmed between the public and private sector actors that provide clarity of roles & responsibilities. A US MNO noted that combined RSU/SCs are possible product wise but are some time away due to the needs for a collaborative business model that clearly outlines the return-on-investment.
    - From a maintenance perspective, there are challenges around the availability of suitably trained technicians. T-Mobile highlighted that technicians are not necessarily flexible to make carry out servicing and maintenance on any MNO equipment and the same is true for roadside infrastructure.
- A vehicle OEM noted that ROs may not want to have MNOs in the middle of their operational business models, and vice versa. These stakeholders traditionally operate very different business models, which is a gap that needs to be bridged. For example, many public sector IOOs are used to operating as ‘cost centres’ that spend money. In order to investigate multi-use, they may need to consider operating more like a business from a revenue perspective.
- The convergence of supporting safety needs at the same time as multi-use may pose challenges. A road operator noted that when federal funding is being used, there are limitations on what it can be used for i.e. transportation related services. While they recognise that there could be an opportunity for offering additional premium services or multi-use of information, this is challenging for any public sector IOO that has a societal focus and accountability for equity.
- Small cells do not have the same coverage area as RSU’s and hence may not be a good combination.

6 Deployment Costs

A cost analysis of the deployment options presented in Section 3 has been carried out. The focus is on the cost to deploy components on the roadside of the V2I system, while cellular data costs are also included. Costs associated with the vehicle, cellular infrastructure and central backend ITS systems are not included. The cost analysis builds on two previous 5GAA reports that considered the costs of deploying dedicated RSU-based and cellular communications [3] [35], a comprehensive review of other material and data sources, and feedback from stakeholder engagement carried out in this study. The analysis in this report extends the scope of the previous studies by considering both cellular (Uu) and fibre backhaul costs, the infrastructure upgrades costs to existing traffic management systems, and potential cost savings from joint deployment of small cells with RSUs or RSI upgrades. Costs that are not included in the analysis are described in Annex 2.

6.1 Costs considered in the analysis

The analysis includes calculations of the cost of reaching full coverage by 2035 for each of the different V2I deployment options. Full coverage is defined as every section of the road network having access to C-ITS services. For Option A, full coverage means complete cellular coverage along the road network and suitable connectivity and processing capability in existing RSI so it can be part of the V2I ecosystem – enabling V2N2I communication. For Options B, C and D, RSUs are deployed at a fixed number of sites that correspond to the number of intersections and ITS infrastructure that exists along the road network [2]. The remaining road network (over 90%[20]) outside of range of these RSUs has cellular coverage.

[20] Based on assumed coverage of fixed number of deployed RSUs deployed and total road network length in EU and US

Low, Central and High scenarios have been developed that reflect expected variation in certain data inputs or assumptions, including RSU equipment and installation costs, fibre backhaul installation costs and existing backhaul availability at RSI/RSU sites. Sensitives were also explored around small cell deployments and the proportion of new backhaul type (wired/wireless). More detail on the scenarios and sensitivities can be found in Annex 2.

Costs of full deployment have been calculated for Europe and the US, and are split into the cost component groups presented in Table 6-1. Option A incurs RSI, backhaul and data costs but no RSU costs. Options B, C and D also have direct communications capability, and so there is an additional cost for deploying RSUs. The cost impact of joint small cell and RSU joint deployment in urban areas is also explored from the road operator perspective. Where joint deployment is assumed, there is potential to share costs related to backhaul, maintenance and hardware installation costs. Joint deployment is explained further in Section 6.1.3.

Table 6-1. Cost component groups included and excluded in the cost analysis

Component	Brief description
Included	
Roadside Units (RSUs)	A communications unit that supports direct and mobile network communications. RSUs are connected to the network through a backhaul (wired or wireless), which can be shared with existing roadside infrastructure when co-located. Assumed all RSUs are integrated into existing infrastructure in calculations.
Roadside Infrastructure (RSI)	Any installed road traffic management equipment that conveys information to travellers or generates data. Examples of roadside infrastructure include traffic lights, variable message signs, sensors and cameras.
Backhaul	The method of transferring information between RSUs/RSI and a central backend. Can be either via wired cabling (i.e. fibre) or through wireless cellular data transfer.
Data Transfer	Messages delivered between vehicles and infrastructure via Uu incur cellular data costs.
Excluded	
In-vehicle system (OBU)	C-ITS hardware (i.e. communication chipset) on-board new vehicles. Vehicle costs are not the focus of this study and are out of scope.
Cellular infrastructure	Significant investment has already been made in mobile network equipment in both the EU and US. Costs for cellular infrastructure would be incurred regardless of V2I and are out of scope.
Application (software)	Aftermarket and in-vehicle applications are needed to deliver the service to the end-user. There is not yet clarity on either the magnitude of this cost or how it would be allocated.
Central backend system	A central ICT system is required to support delivery of V2I services by processing data and monitoring events related to vehicles and roadside infrastructure in the V2I service ecosystem. There is not yet clarity on either the magnitude of this cost or how it would be allocated.

In addition to the total investment required for full coverage, a secondary analysis considers the costs for a cellular system per mile, and for RSUs, deployment on a per unit basis (Section 7.3). These are useful metrics for road operators when considering their specific deployment scenarios, with Uu typically used to provide coverage for larger expanses of the road network, while RSUs are often deployed more sparingly to provide intermittent direct communications coverage at hot spot locations[21] within a road network or along a connected corridor.

The CAPEX and OPEX costs for each component group is described in the following sections and Annex 2.

6.1.1 CAPEX – Infrastructure costs

Road Site Units (RSU)

CAPEX components consist of the equipment, installation and design and planning costs, using data from previous studies [3] [35]. Options B and C are assumed to have the same costs for equipment and the wider installation [35]. One supplier commented that the costs are very similar, although another technology provider highlighted that combining cellular with PC5 would be more cost effective than with 802.11p. Based on our engagement with stakeholders, the additional cost for dual-mode RSUs is expected to be small and is estimated at less than 5%.

RSU installation costs are expected to vary considerably in the field due to differences between RSU sites [2]. A system integrator stakeholder commented that they will classify sites as 'low, medium, or high' reflecting the relative challenge and subsequent cost of that installation. A deployment activity of multiple RSUs will usually include a mixture of sites. The low and high scenarios (Annex 2) in this analysis consider this variation. Stakeholders have shown a strong preference to collocate RSUs with existing infrastructure, and so deployment of RSUs in Option B, C and D are assumed to be limited to the number of existing RSI, with the remaining coverage to connect with vehicles being provided via Uu.

Roadside infrastructure (RSI)

For the RSI to generate and report appropriate V2I messages to backend systems (or vehicles), the local controller in the hardware cabinets may need to be upgraded or additional processing units need to be installed [3]. A single upgrade cost has been assumed for RSIs, which is relevant across all Options [2]. For the purpose of the modelling, the whole cost for RSI upgrades has been considered.

According to feedback received from road operators, in some instances the RSI upgrade cost may be covered by different budgets related to other activities, including the routine upgrade at end-of-life or upgrades as part of broader ITS initiatives. Infrastructure management strategies can also be updated to include C-ITS related upgrades during infrastructure modernisation, for example as has been done in Michigan.

Backhaul

It is desirable to have RSUs and RSI operating within a V2I ecosystem to report back to a central monitoring system, and so backhaul communication costs are considered across all Options. In some very specific cases, it may be possible to deploy RSUs that operate locally without backhaul, but there is general agreement among stakeholders that the intention is to have connected RSUs. For example, Tennessee DOT guidance states that the goal of each RSU deployment is to ensure the following communication is established [36]:

- Communication between RSU and traffic signal controllers (if applicable)
- End to end communication between RSU and TDOT's network
- End to end communication between RSU and SCMS digital certificate server for certificate request and renewal.

A proportion of installation sites are assumed to already have access to backhaul communications, therefore, no backhaul costs are included at these RSU deployment sites and costs to connect RSUs

[21] Locations where parameters such as average daily traffic and roadway geometry, and the desired use case may justify the selection of direct communications technology to deliver the V2I service.

are assumed to be included in installation costs. In the remaining installation sites, either wired or wireless backhaul is assumed to be needed. Wired backhaul has a higher CAPEX compared to cellular [2], but cellular backhaul will incur ongoing data transfer costs. In the case of cable leased services, the RO would incur higher ongoing leased costs rather than upfront CAPEX costs, although this distinction is not captured in the calculations.

As with RSUs, fibre backhaul installation can vary considerably from site to site depending on extent of civil works required to connect the equipment to a wired network [2]. Low and high scenarios include a consideration of this variation. Feedback from stakeholders also highlighted the difference that can exist between deployment environments. All RSUs deployed by Virginia DOT are connected to fibre and they own a good fibre network, so there is little incremental installation cost apart from power. There are also ongoing actions to regenerate ITS sites, and a data access centre is already being paid for. In other cases, there may be a lack of wired network and no suitable backend system to connect with.

6.1.2 OPEX – Operation and maintenance costs

Road Site Units (RSU)

RSU maintenance is calculated as 5% of CAPEX, while power consumption and security certificate licence are included as 'per RSU' costs. An annual licence fee per RSU is assumed to be paid by the RO to cover the costs of subscribing to a SCMS and maintaining the security certificates. Stakeholders suggested that data volumes associated with certificate distribution are expected to be small and so these are assumed to be included within any cellular data costs for backhaul. No additional costs are considered for security for Option A, as communications over cellular networks are protected using non-compromised state of the art security specified by 3GPP. Physical security of roadside equipment (such as anti-theft or -damage) is assumed to be accounted for in RSU / RSI equipment, installation and maintenance costs.

The cost for replacement units after 10 years (assumed lifetime) is annualised and presented as a yearly OPEX cost. Mid-lifetime upgrade of RSUs (i.e. 802.11p to 802.11bd or LTE-PC5 to NR-PC5) are applied in urban environments. Considering the greater density of intersections in urban areas, where the safety critical V2I services are mainly deployed and traffic is higher, these sites are assumed to benefit the most from technology upgrades. Mid-lifetime upgrade cost is assumed to be 25% of the equipment and installation costs, annualised over a 5-year period.

Roadside infrastructure (RSI)

Only maintenance costs are considered, calculated as 5% of CAPEX.

Backhaul and Data transfer

Where cellular backhaul is used for RSIs in Option A, and RSUs in Option B,C and D, costs are incurred for data transfer via the cellular network. Although RSUs are assumed to be collocated with RSI in the field **only one backhaul cost is included** to avoid double counting. This is supported by stakeholder feedback that confirms separate backhaul would not be used.

6.1.3 Joint deployment

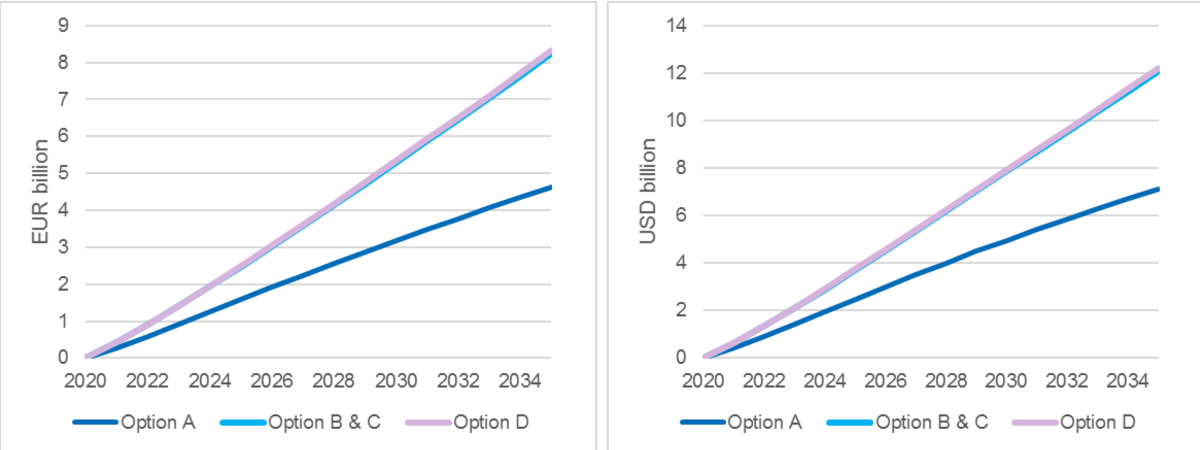
Section 5.3.2 on joint deployment describes the synergies that exist between small cell and roadside equipment installations and operations. Small cells can potentially share the backhaul, hardware installation and general maintenance costs with IOOs when co-located with RSUs or RSI. In the calculations, a cost saving is applied to each of these costs in instances of joint deployment. As the studies' focus is on the costs to the road operator, the analysis does not consider the infrastructure costs borne by the MNO that are not related to V2I, although there would be an equivalent cost saving for the small cell. Viable business cases for densification are primarily relevant to urban areas and so a proportion of urban installations are assumed to be suitable for joint deployment. In line with the expected roll out of 5G and new revenue streams for cellular, the percentage of urban sites that may be suitable for joint deployment increases throughout the analysis period. Stakeholders agreed that the lifetime of small cells is similar to the lifetime of RSUs.

7 Results of Cost Analysis

7.1 Cost comparison

Figure 7-1 below presents the total estimated costs for deployment of the four options to reach 100% coverage in 2035.

Figure 7-1 Cumulative cost comparison between options in central scenario



In each Option, 100% road coverage is assumed to be reached via Uu while in Options B, C and D, full Uu coverage is complemented by additional RSU deployments at existing RSI sites across the road network. There is a linear increase in cumulative costs through to 2035 that reaches around EUR5 billion / USD7 billion for Option A and EUR8 billion / USD12 billion for Options B, C and D. The higher costs for options B, C and D are driven by the additional upfront and ongoing costs for RSU equipment that is collocated with existing RSI across the road network. Costs for options B and C are the same, while Option D is marginally higher. The higher cumulative cost in the US compared to Europe is a result of the larger road network.

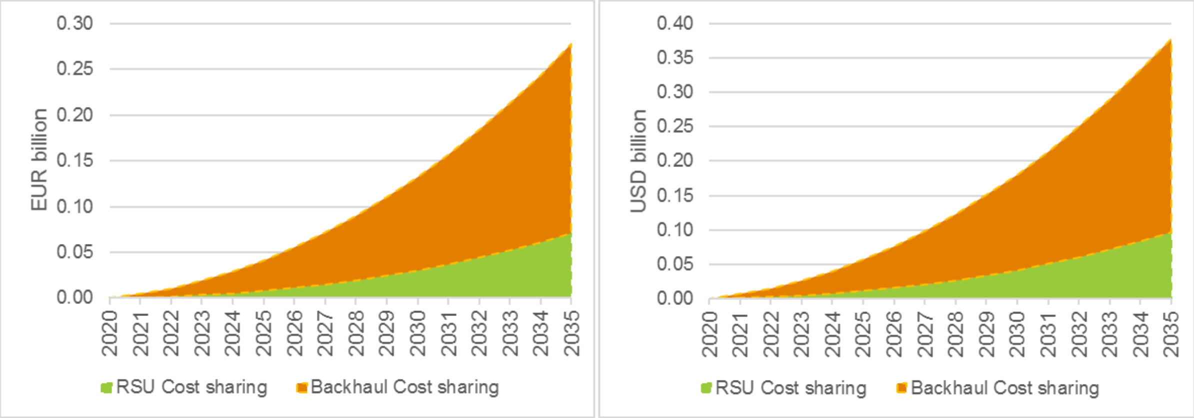
When comparing these costs, there must be recognition that the higher costs incurred in Options B, C and D may realise greater benefits. In individual deployments, a single communication technology may be able to deliver the bundle of desired use cases but at the national/international scale, deployment that includes complementary direct and mobile network communications will support the delivery of a greater range of services (see Section 4) and provide more flexibility.

A theoretical scenario of reaching 100% road coverage with direct communications options (Options B, C and D) has also been considered where RSUs are deployed along the whole road network. This results in huge numbers of deployed RSUs (over 4 million EU and around 5 million US), creating very high CAPEX and OPEX costs for these options, of around EUR70 billion and USD90 billion (see Annex 2 for more details). At the national and international level, this extreme scenario shows the high costs associated with attempting to get full or very high road coverage with only direct communications and highlights the benefits of having V2I systems that combine direct communications technologies with mobile network communications.

7.2 Cost sharing analysis

Joint deployment of urban RSUs with small cells shows cumulative savings of around EUR275 million / USD375 million by 2035 for the Options B, C and D. The breakdown of the cost savings for Option B is shown in Figure 7-2 below. Figures for the remaining options can be found in Annex 2. The main component of the cost sharing savings (EUR210 million / USD280 million) is attributed to backhaul of the urban RSUs where large CAPEX costs of the fibre installation, could be shared with the MNO. RSU CAPEX and OPEX cost reductions are also achieved (EUR70 million / USD100 million).

Figure 7-2 Cost saving potential of joint small cell / RSU deployment Option B



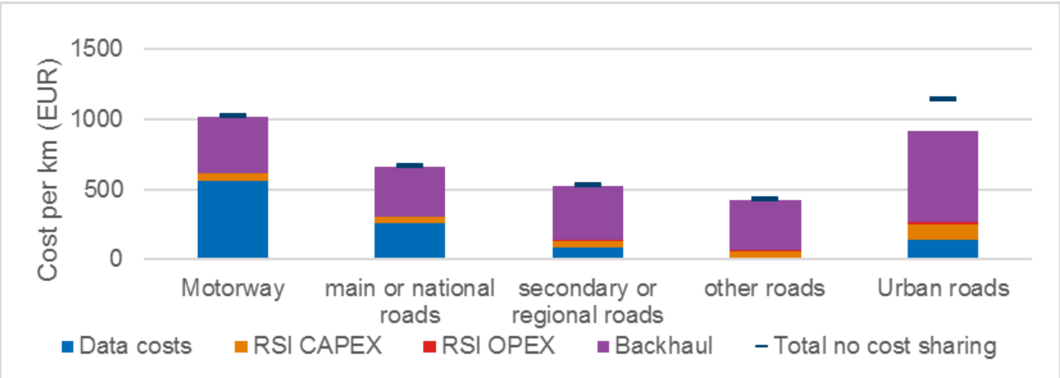
7.3 Breaking down the deployment costs

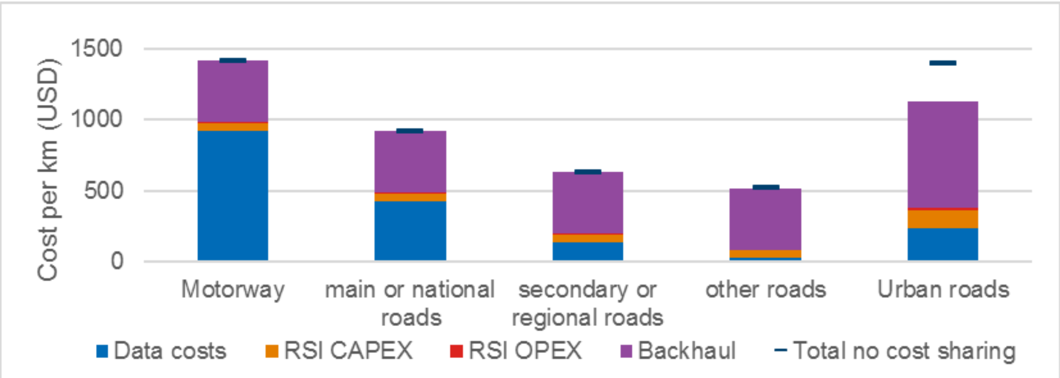
The relative cost to deploy either a cellular system along a km of road network or the per unit cost of RSU deployment has also been analysed to help stakeholders understand the potential magnitude of the cost to equip a length and type of road network, specific to that RO or their scenario.

7.3.1 Pure cellular costs

Figure 7-3 presents the average cost per km for different road types in Option A. The figure represents the in-year cost, and so only one year of OPEX costs are included. The differences in costs between road types are largely driven by the variation in the number of V2I events for each road type, and associated data costs. In urban roads, the higher density of roadside infrastructure results in a higher backhaul and RSI costs, although cost savings are also possible from joint small cell deployment.

Figure 7-3 Option A costs per km for different road types, in EU and US

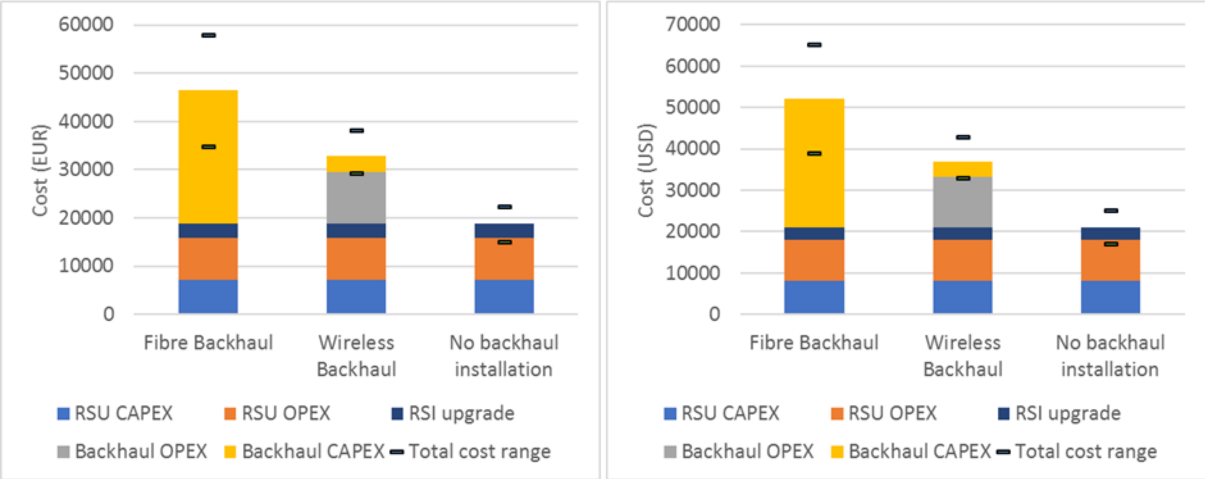




7.3.2 RSU deployments

Figure 7-4 presents the total costs over the lifetime (10 years) of an RSU in three different backhaul installation environments. The figure also shows the total cost range for each installation type, accounting for the variation seen in RSU and backhaul installation costs.

Figure 7-4. Lifetime (10 years) cost per RSU with different backhaul installations, in EU and US



The highest costs can be seen in fibre installations where expensive laying of fibre (backhaul capex) accounts for most of the total cost. There is also significant variation in the costs of fibre backhaul installation reported in the literature [2] [37], which accounts for the majority of the large cost variation. This scenario may exist where RSUs are being deployed in areas with poor cellular coverage or where additional fibre is laid to connect an RSU to a nearby fibre network.

Where wireless backhaul is used, costs are split roughly evenly between backhaul and RSU, with the respective OPEX costs (cellular data and maintenance) accounting for a significant share over the ten-year period. Wireless backhaul may be used in mobile deployment environments (i.e. roadworks trailers) or when there is no existing fibre to connect with and the costs to lay new fibre are too high. In the lowest cost installation option, an existing wired backhaul network is assumed to be available, meaning only RSU costs are incurred. In the wireless backhaul and no backhaul scenarios, the range in total costs is driven by variation in the RSU installations. Costs reported in available online resources [38] and feedback from stakeholders highlighted the variations in the RSU cost component, which are driven by different installation effort required. The RSU equipment costs does not vary significantly.

In a scenario where RSUs are deployed along a stretch of road network to provide uninterrupted coverage, total installation costs can also be influenced by the range of RSUs and resulting intervals. RSU intervals may differ between road types, with shortest intervals along urban roads and motorways (~1 RSU per km), where a higher bit rate and a more reliable connection is needed to support the high number of V2I events per km. An improved range of PC5 compared to 802.11p RSUs has been demonstrated in radio performance tests [39], which could result in lower deployment costs for Option C where a length of road network is being equipped with direct communications coverage. Furthermore, if the deployment activity has a fixed number of deployment sites, the larger communications coverage area of a PC5 RSU could also be a benefit.

8 Conclusions and Recommendations

8.1 Conclusions

Considering the information that has been collected in this study, there is clear variation in the views and visions of stakeholders and in the local environment of deployments, which ultimately result in a range of activities that focus on different V2I use cases and different communication technology solutions. Some road operators are focusing on RSU deployments and others on mobile network communications, while many are adopting hybrid approaches. It is recognised and understandable that deployments are emerging from different technology starting points, and work should focus on developing comprehensive V2I systems that use mobile network technologies augmented by direct communications RSUs, and support interoperability and data sharing in the backend - bringing the greatest value and benefit to all stakeholders.

The economics of deployment options is a central topic in decision making, whether it is the public sector weighing costs and benefits or a more commercial business model considering ROI. The analysis shows that a pure cellular deployment option is lower cost compared with RSU options, which is supported by several existing deployment activities that have focused on cellular as a quick and low cost ‘route to market’. This approach enables the delivery of many V2I services and provides a wide geographic and fleet coverage. The study also highlights the nuances that exist between deployment environments, and the cost implications particularly for RSUs. Variation in aspects such as backhaul and cellular network availability make it very challenging to apply a common cost or technology approach across different deployment activities.

Pure Uu-based network is seen by some ROs and stakeholders as an attractive and a cost-effective starting point for providing V2I (V2N2I) services to a large user base. However, a key consideration for many ROs and other stakeholders is whether Uu can support the safety critical services (typically use-cases at intersections). Based on the feedback received through this study, a risk-averse view is often taken by ROs where guaranteed performance for such services can only be currently delivered via direct communications systems. There are clear real-world examples that show, technically, Uu can deliver these services, with latency requirements of up to 100ms, but these tend to be limited and do not necessarily guarantee the ability to maintain such levels of service across the entire road network. It is possible that cellular developments such as NR and MEC could address some of the performance drawbacks of current LTE and could enable more use cases and services to be delivered via Uu in the future. However, at present these services are not widely available and it is not clear to what extent they could fully overcome the limitations at a national or regional level and the potential costs associated with implementing these. Presently, the use of RSUs can help address some of these limitations through targeted deployment at sites where such use cases would be most valuable.

The additional costs to deploy and maintain RSUs in a pure cellular system are shown to be manageable (66% greater by 2035) when restricted to sites where the RSU can be collocated with existing infrastructure. Although, as described earlier, the exact costs are heavily dependent on the specifics of the deployment sites and access to existing backhaul. This additional investment enables the delivery of a wider range of use cases in those locations, making them ideally suited for focused deployment of safety V2I services. In all cases, local conditions such as cellular coverage, the existence of a fibre network and road transport issues are other important factors that influence decision making. With costs accruing linearly for every additional RSU deployed, the analysis also highlights that comprehensive coverage of RSUs across the road networks results in very high costs, which are unlikely to be justified and is not an approach supported by stakeholders.

Over the last few years, regulatory uncertainty in the EU and US has been an important theme influencing decision making around direct V2X communications. However, following a decision on the FCC NPRM and a continuation of the neutral stance in Europe there may be increased confidence in the market, resulting in more significant commitments from vehicle manufacturers and road operators over the next five years. As the PC5 direct link is highly integrated with Uu in the C-V2X solution, and there is a clear evolution path to 5G with backwards capability, C-V2X appears to provide a more future proof solution compared with the combined 802.11p/Uu option. In the US, it is possible that the pending FCC decision may tip the balance towards C-V2X. There is also more interest among OEMs in the C-

V2X solution, although there is no aligned view across the automotive sector - so with many road operators expected to respond flexibly to accommodate technology decisions made by OEMs, there will likely be a continued mix of direct communications technologies in deployments in the short term.

Another potential solution is a dual mode RSU, but it is not yet clear whether there is appetite in the market for this beyond a few initial years. Analysis presented in this report shows that the additional cost of a dual mode RSU (802.11p and C-V2X) is minimal, yet it is not the preferred solution across ROs engaged in this study. This may be due to concerns and assumptions around higher costs, the market availability or ability of technicians to service both technologies.

There are numerous examples of organisations and projects focused on supporting effective cooperation in V2X, and these must continue. Trust and cooperation can support interoperability, minimise risk of stranded infrastructure assets or wasted public funds, ensure maximum benefits to most road users and bring together the necessary data. Cooperation is also needed to unlock viable business models and leverage public-private investment, which are generally seen as prerequisites for sustainable, wide scale deployment. The potential for cities and MNOs to capitalise on synergies in motivations and activities (i.e. joint small cell deployment) is a prime example of where opportunities exist.

8.2 Recommendations

A general recommendation for all stakeholders is to engage with activities and organisations that support cooperation and facilitate knowledge sharing. Some key recommendations for specific stakeholders, based on the results of this study, have been outlined below:

Road infrastructure owner/operators

- Focus on deployment that can deliver guaranteed, early benefits, perhaps targeting specific fleets or use cases where compatible vehicles are likely to be available and V2I services will be used by the target users. Input from stakeholders highlights the negative impact of uncertainty around direct communications technologies at the national level. Road operators should focus on the deployment conditions over which there can be more control at a local level.
- When deploying RSUs, consider deployment of dual mode RSUs to ensure future proofing and minimising the risk of stranded assets or wasted funds. The additional cost of doing so appears to be minimal.
- Contribute towards the development of interoperable backend systems that can support services delivered over mobile network and direct communications and where cost is a barrier, starting with cellular deployment can be a more feasible ‘route to market’.
- Leverage synergies with other industries and make the most out of the valuable assets and utilities that are owned. There are clear opportunities for road operators, and more broadly the public sector, to work with the private sector, particularly in urban environments where smart cities will demand connectivity and availability of data.
- Consider novel business models and engagement with organisations such as MNOs that benefit from MNO’s technical skills and experience in deploying and maintaining communications equipment.
- Seek to understand the status of their (RO) infrastructure and assets, in terms of the availability of backhaul solutions and the need to upgrade existing road-side equipment that is part of the V2I ecosystem. Results from the cost analysis and engagement with stakeholders in the study, emphasises the importance of backhaul from a system functionality and cost perspective. An understanding of the status of connectivity networks available and roadside infrastructure will help ROs to understand potential costs and optimise the planning of service deployments.

Central government

- Maintain financial support and availability of financial instruments across all deployment activities. National funds will continue to be needed for R&D activities as technologies develop and the outputs of this study show that support is still needed to bridge the gap between R&D and wider scale commercial infrastructure procurement. Examples presented in the report also highlight how public sector funding can provide the catalyst to encourage cooperation and leverage private sector investment.

Vehicle manufacturers

- Continue to engage with ROs on deployment activities and clearly communicate roadmaps for vehicle deployments, where possible. For OEMs that manufacture/manage fleet vehicles (e.g. trucks, taxis, buses, emergency vehicles), target specific use cases with ROs.

Mobile network Operators

- Work with the public sector and vehicle manufactures to identify viable business models that can support the delivery of cellular V2I services and the integration of new cellular development (NR, MEC etc) into the V2I ecosystem. Analyse the synergies of joint small cell/RSU deployment.

For suppliers and technology providers

- Continue to work closely with clients to offer innovative solutions that can help to address uncertainty and risk. Feedback from stakeholders show that the potential for dual communication units is there, but it is too early to say whether there is the demand. Availability of such units at competitive prices will help to mitigate market uncertainty in the RSU space and will enable ROs to invest in RSU deployment without risking backing the "wrong" technology.

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10 Abbreviations

Term	Definition
CAPEX	Capital expenditure
C-ITS	Cooperative intelligent transport systems
C-V2X	Cellular Vehicle-to-Everything (based on 3GPP standards)
DSRC	Dedicated short-range communication (based on 802.11p)
DOT	Department of Transport (US)
FCC	Federal Communications Commission
ICT Infrastructure	Information and Communications Technology Infrastructure
IOO	Infrastructure owner/operator
LTE	Long term evolution
MAP	Map Data
MEC	Multi-access Edge Computing
MNO	Mobile Network Operator
NCAP	New Vehicle Acceptance Programs
NPRM	A notice of proposed rulemaking
NR	New Radio (5G standard)
OBU	On Board Unit
OEM	Original Equipment Manufacturer (vehicle manufacturer)
OPEX	Operational expenditure
PND	Personal navigation devices
PPP	Public private partnership
QoS	Quality of Service
RO	Road operator
ROI	Return on Investment
RSI	Roadside Infrastructure
RSU	Roadside Unit
SC	Small Cell
SCMS	Security credential management system
SPaT	Signal Phase and Timing
UE	User Equipment
V2I	Vehicle-to-Infrastructure
V2N2I	Vehicle-to-Network-to-Infrastructure
V2P	Vehicle-to-Pedestrian
V2N2P	Vehicle-to-Network-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2N2V	Vehicle-to-Network-to-Vehicle

11 Annexes

A.1 Annex 1 – Stakeholder Engagement Activity

The objective of the stakeholder engagement activity was to gain insights from previous, current and future deployment activities, including the factors that influenced the decision making and the key takeaways. The stakeholder engagement activity was conducted between February 2020 and April 2020. Specifically, Ricardo targeted stakeholders in four key groups:

- Public sector agency (i.e. cities, road operators (RO))
- Mobile Network Operators (MNO)
- Suppliers/Technology providers
- Vehicle Manufacturers (OEM)

We note that, although the groups do not represent all possible stakeholders involved in V2X, those listed are the most relevant for V2I infrastructure deployment and costs.

A questionnaire was designed to facilitate the conversation and given to stakeholders ahead of time to ensure they had sufficient time to prepare. Questions in 5 sections were developed and tailored for each stakeholder group:

- Background and motivations for V2X
- Involvement with the four options considered in this study
- Financial considerations for each option
- Multi-use of V2X RSUs
- Cellular network considerations.

In total, 16 telephone interviews were carried out and 3 face-to-face interviews were conducted at a 5GAA conference in February. 6 stakeholders that were not able or willing to complete a phone interview provided written responses.

In total, Ricardo received contributions from 25 stakeholders, listed in the table below

List of stakeholder organisations contributing to this study

Organisation	Engagement type
Public sector / road operator	
Anon (US city)	Written responses
City of Turin, Italy	Written responses
Croatian Ministry of Marine, Transport and Infrastructure	Written responses
Czech Motorway and Road Operator - Czech Transport Ministry	Telephone Interview
Danish Road Directorate	Written responses
Dutch Ministry of Infrastructure and Water Management (I&W), Rijkswaterstaat (RWS)	Telephone Interview
Finnish Transport and Communications Agency Traficom	Telephone Interview
Michigan Department of Transportation (MDOT)	Telephone Interview
San Diego Association of Governments (SANDAG)	Written responses
United Kingdom, Department for Transport	Written responses

Virginia Department of Transportation (VDOT)	Telephone Interview
Mobile Network Operator (MNO)	
AT&T	Telephone Interview
Deutsche Telekom	Telephone Interview
KPN	Telephone Interview
Telstra	Telephone Interview
Verizon Wireless	Telephone Interview
Supplier / Technology Provider	
Danlaw	Telephone Interview
Ericsson	Face-to-face Interview
Huawei	Telephone Interview
Panasonic	Telephone Interview
Qualcomm	Face-to-face Interview
Vehicle Manufacturer (OEM)	
Ford	Telephone Interview
Anon	Telephone Interview
Anon	Face-to-face Interview
Other	
Southwest Research Institute (SWRI)	Telephone Interview

In a separate activity, anonymised responses were received from five RSU vendors on questions relating to demand for different types of units on the market in EU and US.

A.2 Annex 2 – Cost Analysis

Error! Reference source not found. The table below summarises the costs components that are considered in the cost analysis.

Cost considered in Option

Cost considered in Option, and available cost sharing in joint deployment

Not considered in Option

Cost components considered in cost analysis.

Item	Cost element	Cost type	Cost unit	Option A	Option B	Option C	Option D
RSU (802.11 & Uu)	Equipment: box, antenna, wiring, processor and security chip (same for 802.11p and 802.11bd)	CAPEX	per Unit				
	Installation and labour costs	CAPEX	per Unit				
	Design and Planning	CAPEX	per Unit				
	Power consumption	OPEX	per Unit				
	Maintenance	OPEX	per Unit				
	Security certificate license	OPEX	per Unit				
	Annualised replacement cost (Hardware + installation over 10 years)	OPEX	per Unit				
	Upgrade of tech (if required); e.g. 802.11p to 802.11bd	OPEX	per Unit				
RSU (PC5 & Uu)	Equipment: box, antenna, wiring, processor and security chip (same for 802.11p and 802.11bd)	CAPEX	per Unit				
	Installation and labour costs	CAPEX	per Unit				
	Design and Planning	CAPEX	per Unit				
	Power consumption	OPEX	per Unit				
	Maintenance	OPEX	per Unit				
	Security certificate license	OPEX	per Unit				
	Annualised replacement cost (Hardware + installation over 10 years)	OPEX	per Unit				
	Upgrade of tech (if required); e.g. 802.11p to 802.11bd	OPEX	per Unit				

RSU (802.11, PC5 & Uu)	Equipment: box, antenna, wiring, processor and security chip (same for 802.11p and 802.11bd)	CAPEX	per Unit
	Installation and labour costs	CAPEX	per Unit
	Design and Planning	CAPEX	per Unit
	Power consumption	OPEX	per Unit
	Maintenance	OPEX	per Unit
	Security certificate license	OPEX	per Unit
	Annualised replacement cost (Hardware + installation over 10 years)	OPEX	per Unit
	Upgrade of tech (if required); e.g. 802.11p to 802.11bd	OPEX	per Unit
Backhaul	Wired backhaul equipment and installation (fibre)	CAPEX	per Unit
	Wireless backhaul equipment and installation (modem etc.)	CAPEX	per Unit
	Cellular data backhaul costs	OPEX	per Unit
Roadside infrastructure	Upgrade (local controller / processing unit)	CAPEX	per Unit
	Maintenance	OPEX	per Unit
Cellular data costs	Delivery of mobile network communications between vehicle and infrastructure (RO)	OPEX	per bit/ per unit

A.2.1 CAPEX costs

When RSUs are installed in the field, there are different installation challenges with different locations. This is supported by costs identified in the literature [2] [40] [41] [38]. A range of 20% either side of the central scenario cost has been applied to RSU CAPEX in the Low and High scenarios. The total CAPEX for the RSUs in the central scenario is EUR7,200/ USD8,080 for Options B and C. Input from stakeholders indicated that CAPEX costs for dual unit RSUs (Option D) are 3% higher.

The fibre backhaul installation costs can vary between USD20,000 to USD40,000 per RSU [2], while installation costs for wireless backhaul is lower cost [42]. In some cases, there is already backhaul in place and the RSU/RSI unit does not incur the new backhaul costs. A study from the US [2] showed that 70% of nationwide traffic signals would require completely new or significant backhaul upgrades to facilitate C-ITS services, whilst for other ITS infrastructure (i.e. cameras or VMS) the proportion needing new or significant backhaul upgrades was 25%. The study also found that signal controller hardware upgrades would be required in 64% of cases.

A.2.2 OPEX costs

Annual maintenance of RSUs and RSI is calculated as 5% of CAPEX. Power, security certification costs are also included [35] [3]. Replacement costs are annualised over 10 years. In Option A all V2I events are transmitted via Uu, and in the other Options it is assumed to be 50% of events. Annual data costs for cellular backhaul are estimated as USD1,200 from stakeholder input.

A.2.3 Fixed Input Data

The total road network length, along with the RSU deployment density, determines the total number of RSUs required for full coverage. The below table also combines with the average number of V2I events per km per year to determine the data costs at full coverage.

Source: [43] [44] [45]

	United States road network (km)	Europe road network (km)
Motorway	107,193	77,733
main or national roads	644,361	339,887
secondary or regional roads	883,721	1,081,455
other roads	3,119,145	2,414,159
Urban roads	1,910,138	1,572,183
Urban intersections	230,503	189,721

Source: Adapted from [3]

Average number of V2I events per km per year - at full coverage	# / km per year
Motorway	88446300
main or national roads	40568188
secondary or regional roads	12684320
other roads	1974373
Urban roads	21916644

New RSUs will integrate with existing infrastructure and share the backhaul. The number of existing units also determines the number of RSI upgrades required to facilitate V2I services.

Source: Adapted from [38]

Existing roadside infrastructure (# units)	US	Europe
Traffic signals	311000	255976
Other infrastructure	25000	18129

The existing and new backhaul is used to directly determine the number of RSI and RSUs needing backhaul to connect the infrastructure to a central system. As this proportion will vary region to region, sensitivities are provided to give insights into potential high and low-cost scenarios.

Source: [38]

Backhaul requirements	US (central)	Europe (central)	All regions (high)	All regions (low)
Traffic signals with existing backhaul	30%	30%	20%	40%
Traffic signals with no existing backhaul	70%	70%	80%	60%
Other infrastructure with existing backhaul	75%	75%	65%	85%
Other infrastructure with no existing backhaul	25%	25%	35%	15%
Traffic controllers requiring upgrade	64%	64%	Same as central	Same as central
Traffic controllers not requiring upgrade	36%	36%	Same as central	Same as central

The below table provides the sensitivities considered in the cost analysis. As the proportion of new backhaul being cellular / fibre is unknown, a range of values is presented for different levels of cost (high / central / low).

Cost element sensitivity	Low	Central	High	Notes
Proportion new backhaul fibre	25%	50%	75%	
Proportion new backhaul cellular	75%	50%	25%	
Small cell deployment 2035	75%	50%	25%	* relates to cost sharing
PC5 improved range	Yes	No	No	* relates to RSU density

A.2.4 Costs not included in the analysis

Several costs are outside the scope of this study but have been identified as relevant to highlight qualitatively. Stakeholder engagement revealed that a major cost concerning RSUs can be the labour costs associated with the maintenance of the units. The labour costs associated with maintenance are assumed to be included within the general maintenance of RSUs, however, the training of maintenance staff or hiring of additional staff is an additional cost to consider. This would vary significantly based on assumptions for source of maintenance staff and geographic location and so had not been included. Societal costs related to delays due to road closures for installation or maintenance of RSUs / RSI upgrades are also not included. These will be highly variable depending on specific situation, location, traffic conditions and duration.

Two elements that are necessary, regardless of communication technology, are a central backend system and the V2I service application. A central ICT system (e.g. cloud, traffic management centre, PKI, data centre) is required to support delivery of V2I services by processing data and monitoring events related to vehicles and roadside infrastructure in the V2I service ecosystem. These systems are likely to be hosted by OEMs, ROs, third party service providers, or a combination of all three. Where third party service providers are involved, additional costs are incurred, although the magnitude of these costs and how they would be allocated is not yet clear.

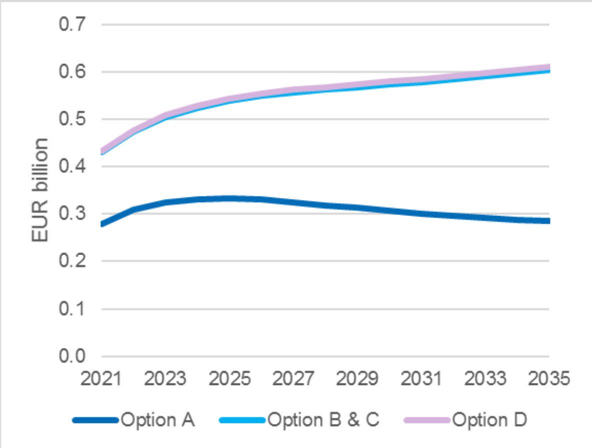
The CAPEX and OPEX for the central traffic management system can vary greatly depending on the scope and sophistication of the system but could account for a large part of the costs of deploying C-ITS [40]. Road operators engaged with reported a range of situations with regards to central systems. While some highlighted the existence of sophisticated systems, others noted that investment would be needed to support V2I, particularly as scale of services increases. A European transport agency noted that a new version of a TMC backend system was already being developed that could support V2I service, but that it was not considered as a C-ITS expense. The central ICT system or application server may be hosted by a third party service provider

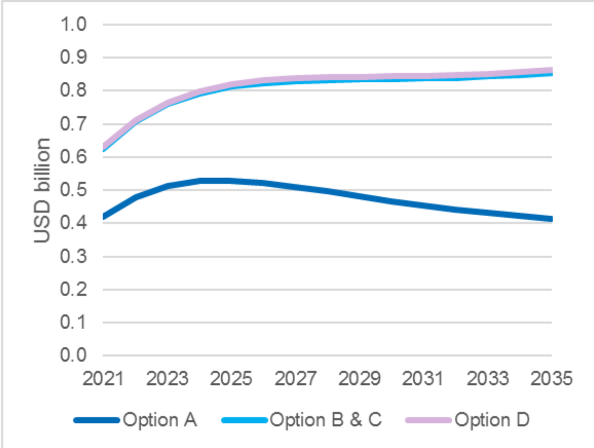
Aftermarket and in-vehicle applications are needed to deliver the service to the ‘user’ (i.e. driver or other road users). These may be applications delivered on a smartphone/aftermarket device or embedded in the vehicle by the OEM. Cities and road operators may integrate the delivery of services with existing applications developed by OEMs or other service providers. However, public bodies may also develop their own applications in-house or through cooperation with other organisations. The costs will vary depending on the nature of the application, the platform it is deployed on and business models used by the developer or service provider. Traficom noted that there are many options in the current market in Finland and so it would not be beneficial to the authorities to develop a new one. The Traffic Management Finland Group have a basic application (Liikennetilanne), but the purpose of this service is to make basic information and open data available.

A.2.5 Cost Analysis Results

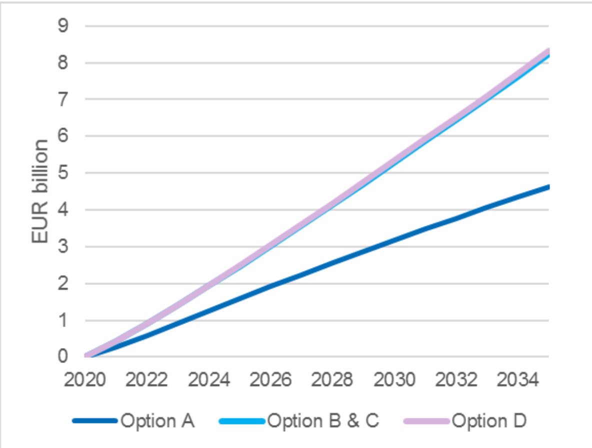
A.2.5.1 Central Scenario

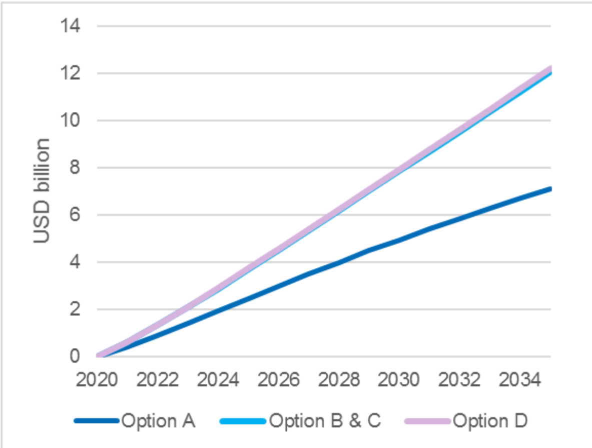
Total in-year costs



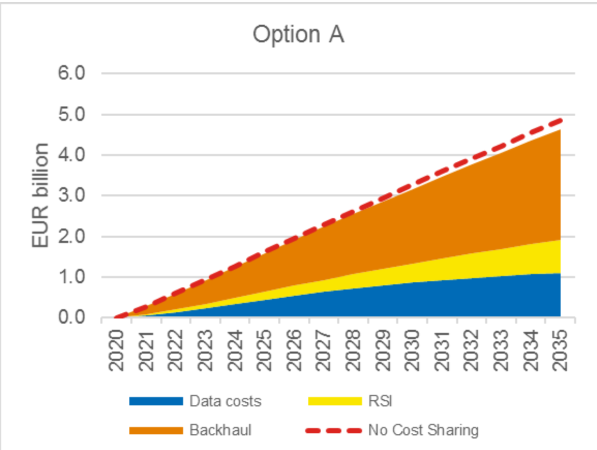


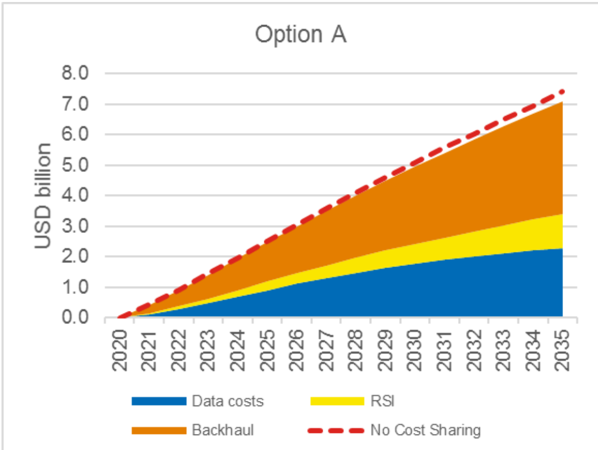
Total cumulative costs

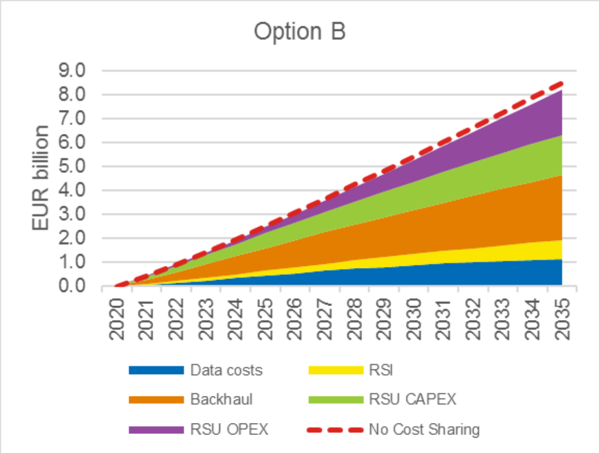


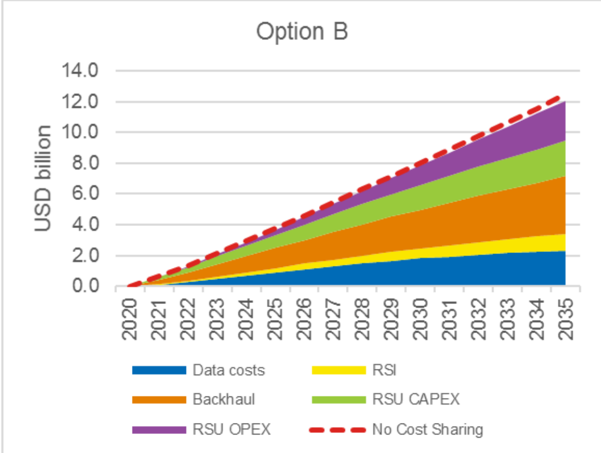


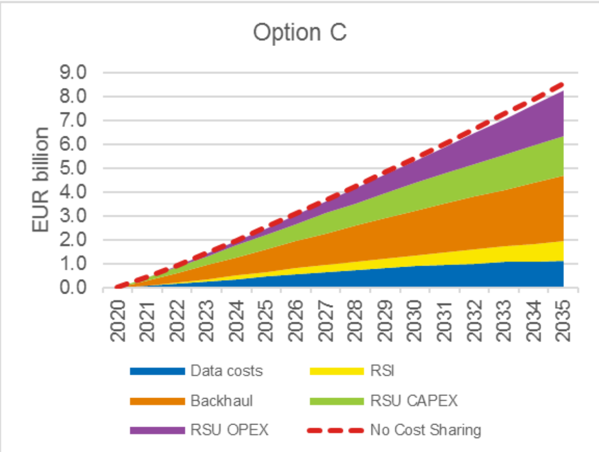
Breakdown of cumulative cost per option

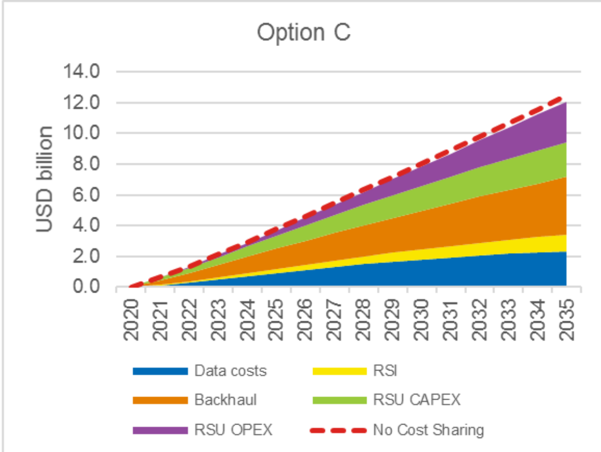


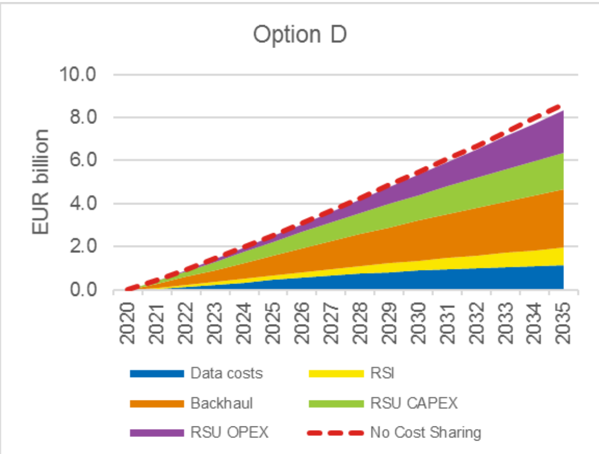


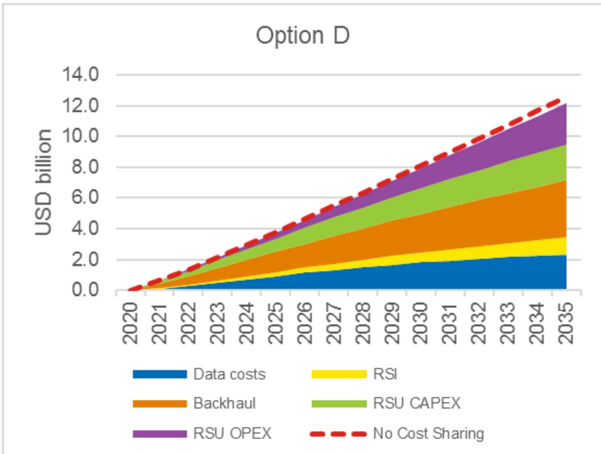

Option B
EUR billion
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035
Data costs
RSI
Backhaul
RSU CAPEX
RSU OPEX
No Cost Sharing


Option B
USD billion
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035
Data costs
RSI
Backhaul
RSU CAPEX
RSU OPEX
No Cost Sharing


Option C
EUR billion
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035
Data costs
RSI
Backhaul
RSU CAPEX
RSU OPEX
No Cost Sharing


Option C
USD billion
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035
Data costs
RSI
Backhaul
RSU CAPEX
RSU OPEX
No Cost Sharing


Option D
EUR billion
10.0
8.0
6.0
4.0
2.0
0.0
2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035
Data costs
RSI
Backhaul
RSU CAPEX
RSU OPEX
No Cost Sharing


Option D
USD billion
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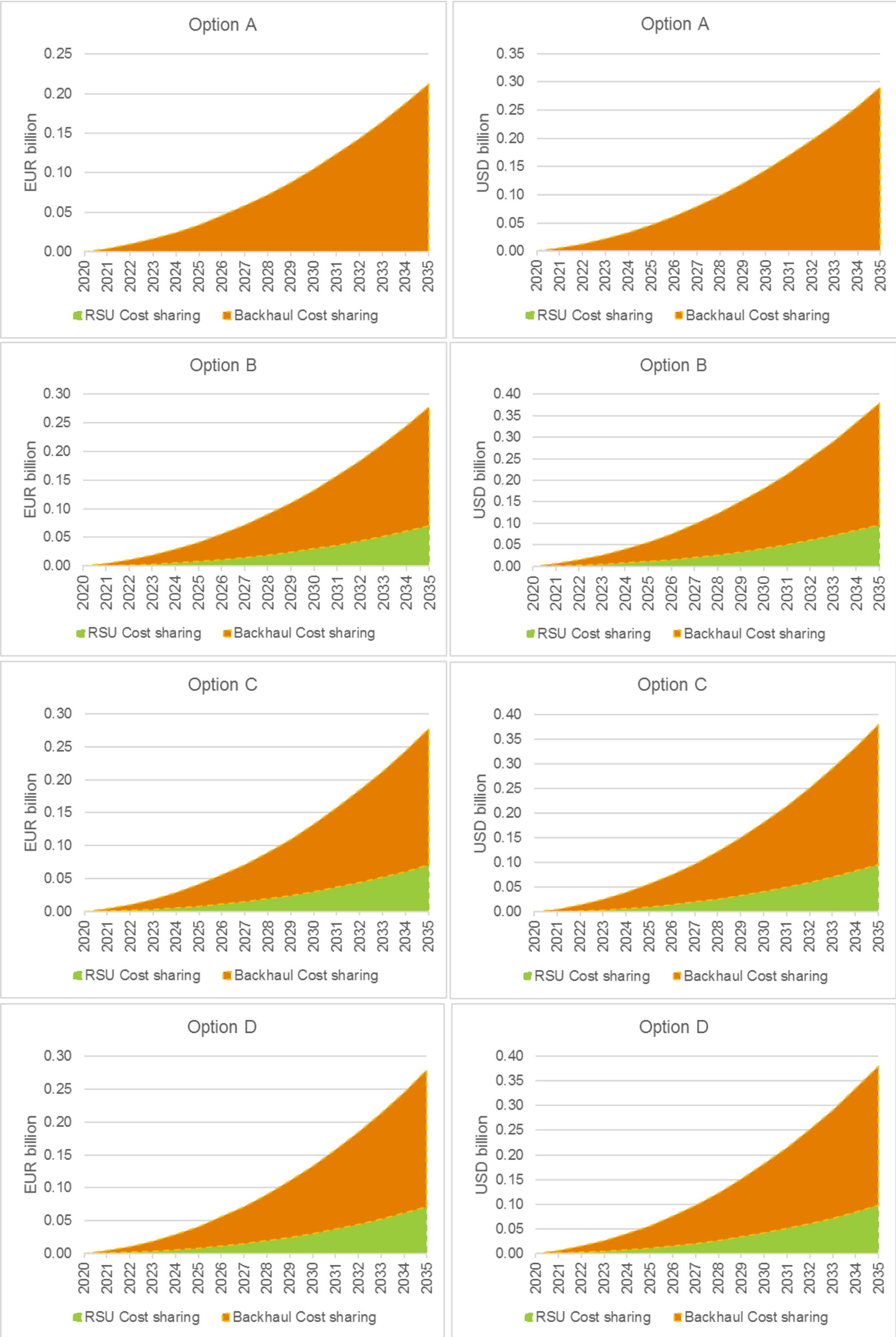
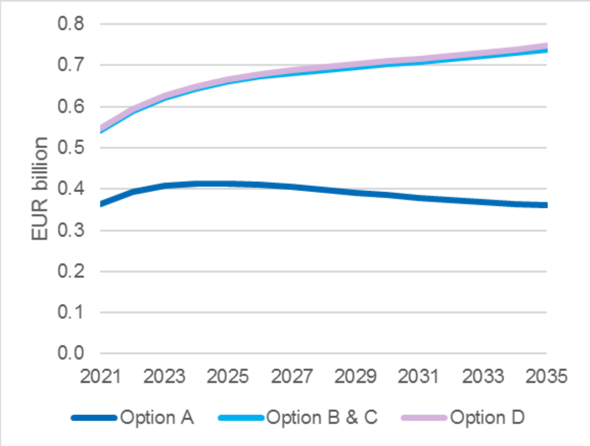
12.0
10.0
8.0
6.0
4.0
2.0
0.0
2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035
Data costs
RSI
Backhaul
RSU CAPEX
RSU OPEX
No Cost Sharing

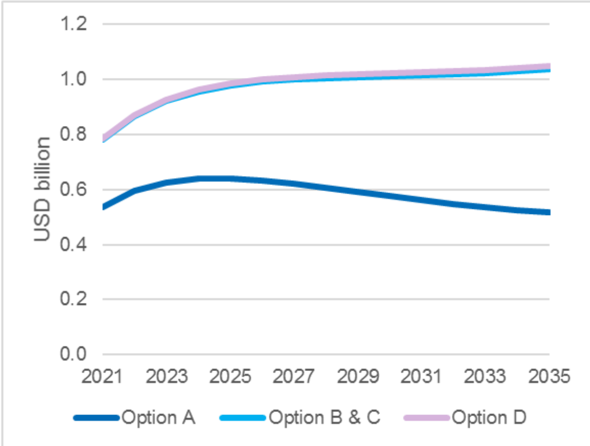
Cumulative cost saving per option



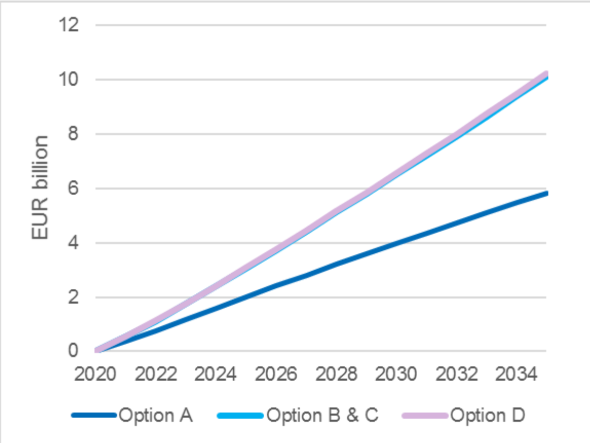
A.2.5.2 High-cost scenario

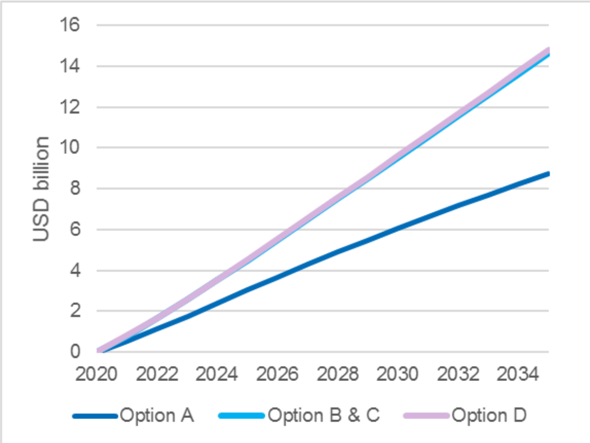
Total in-year costs



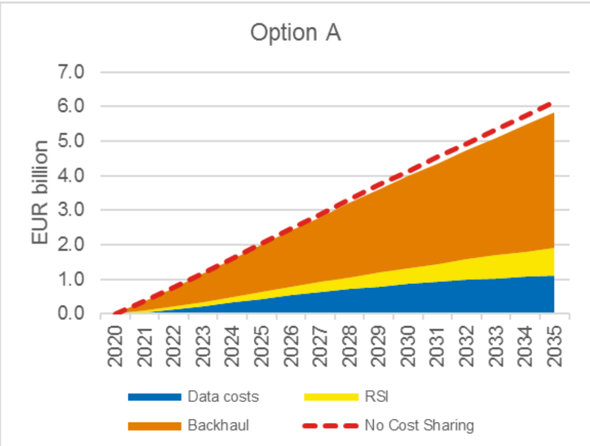


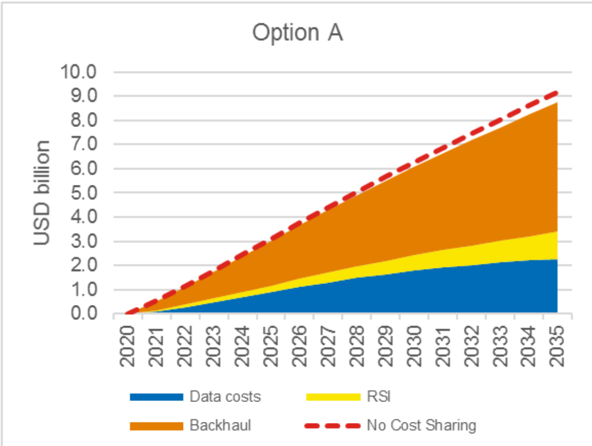
Total cumulative costs

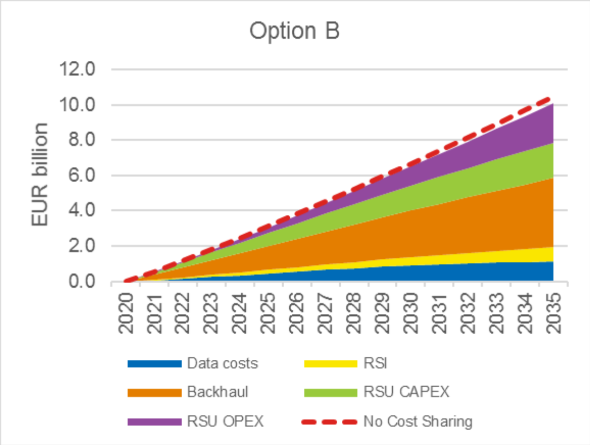


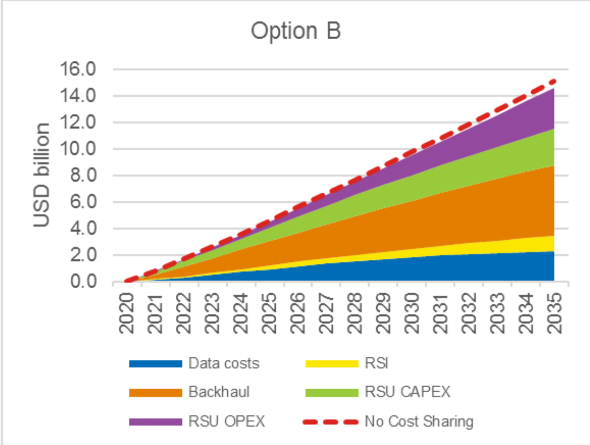


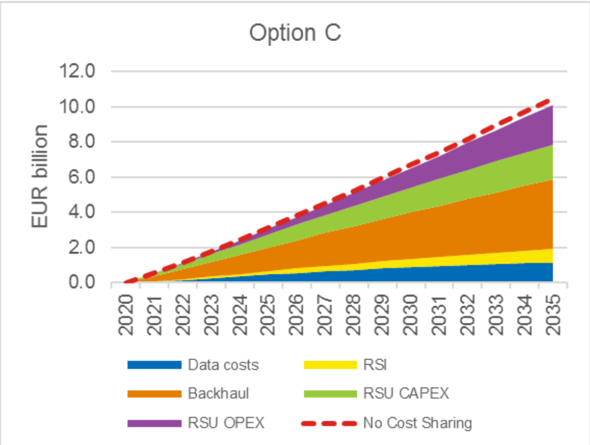
Breakdown of cumulative cost per option

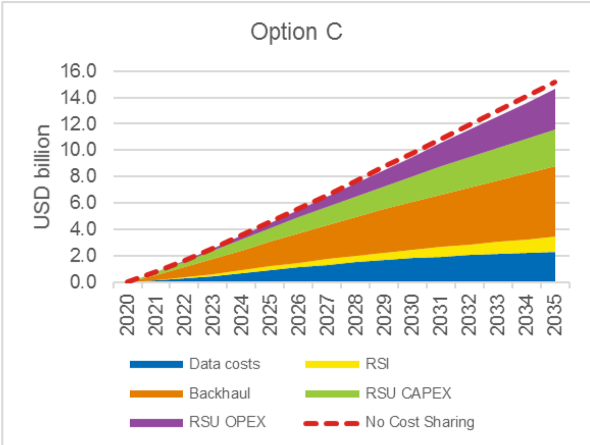


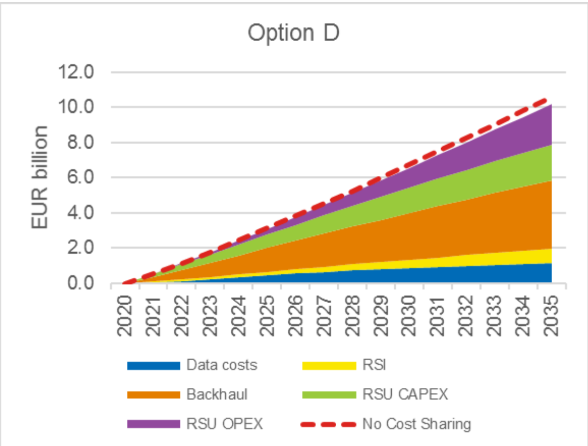


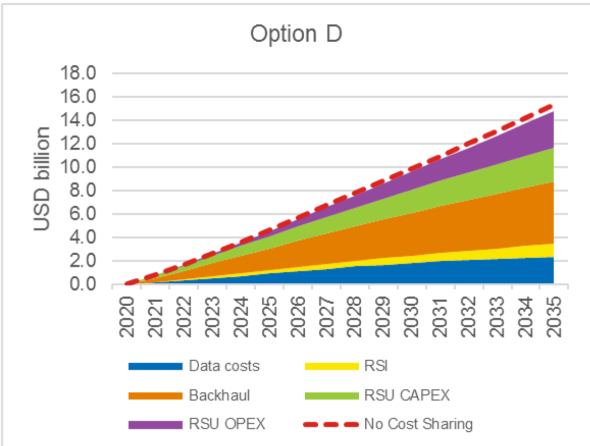

Option B
EUR billion
12.0
10.0
8.0
6.0
4.0
2.0
0.0
2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035
Data costs
RSI
Backhaul
RSU CAPEX
RSU OPEX
No Cost Sharing


Option B
USD billion
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035
Data costs
RSI
Backhaul
RSU CAPEX
RSU OPEX
No Cost Sharing


Option C
EUR billion
12.0
10.0
8.0
6.0
4.0
2.0
0.0
2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035
Data costs
RSI
Backhaul
RSU CAPEX
RSU OPEX
No Cost Sharing


Option C
USD billion
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035
Data costs
RSI
Backhaul
RSU CAPEX
RSU OPEX
No Cost Sharing


Option D
EUR billion
12.0
10.0
8.0
6.0
4.0
2.0
0.0
2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035
Data costs
RSI
Backhaul
RSU CAPEX
RSU OPEX
No Cost Sharing


Option D
USD billion
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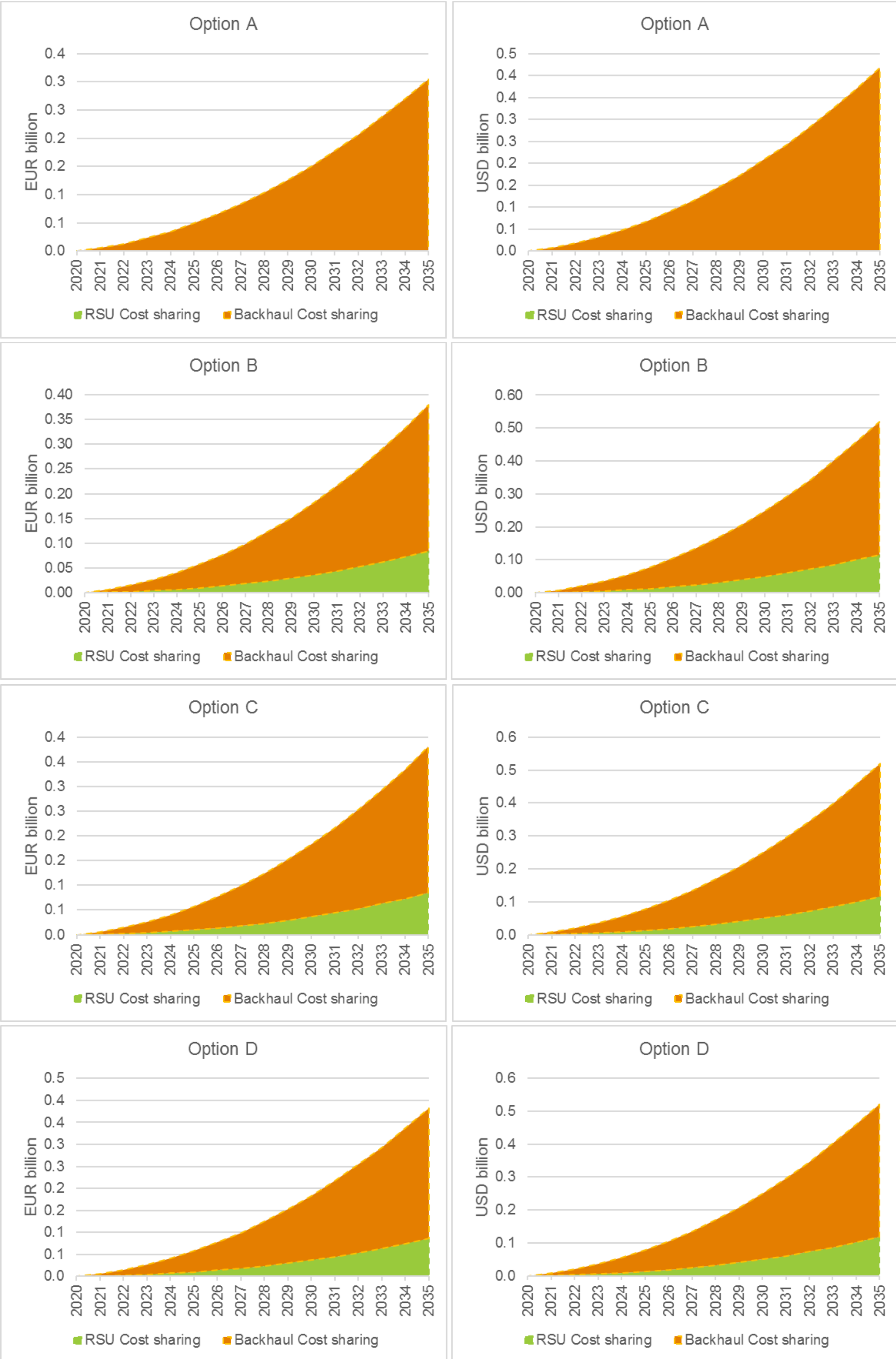
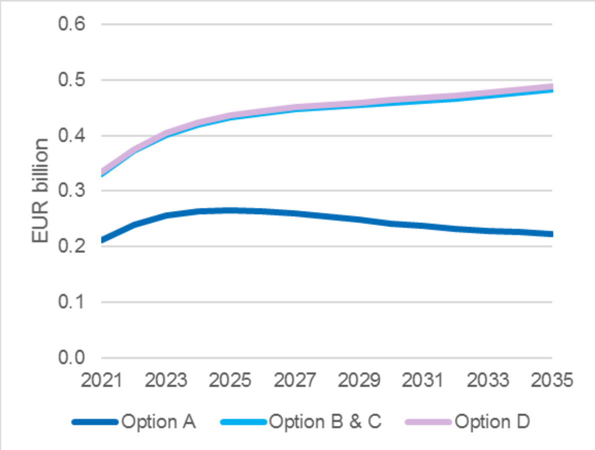
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035
Data costs
RSI
Backhaul
RSU CAPEX
RSU OPEX
No Cost Sharing

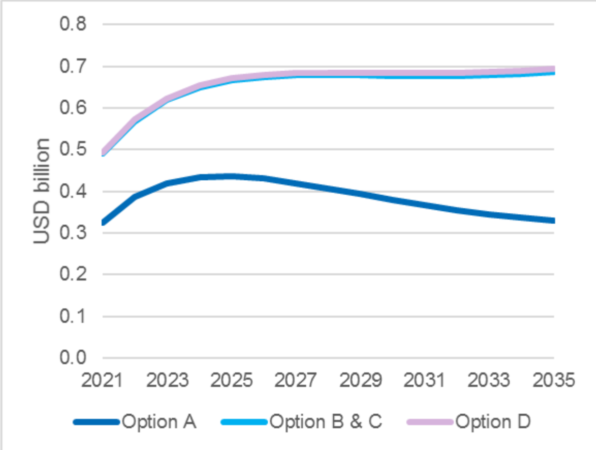
Cumulative cost saving per option



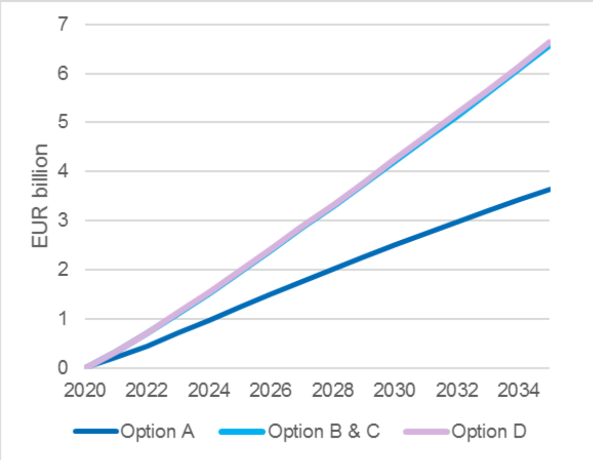
A.2.5.3 Low-cost scenario

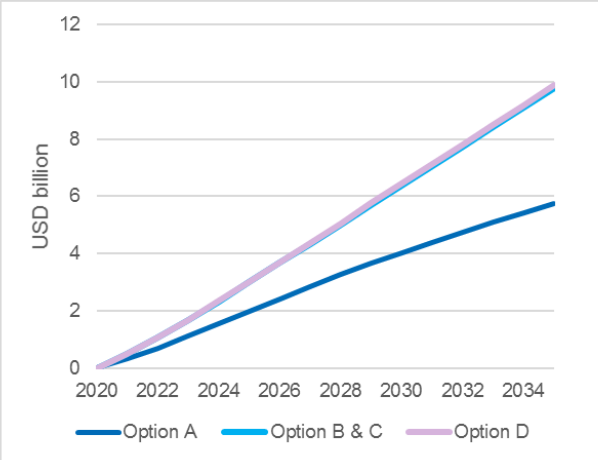
Total in-year costs



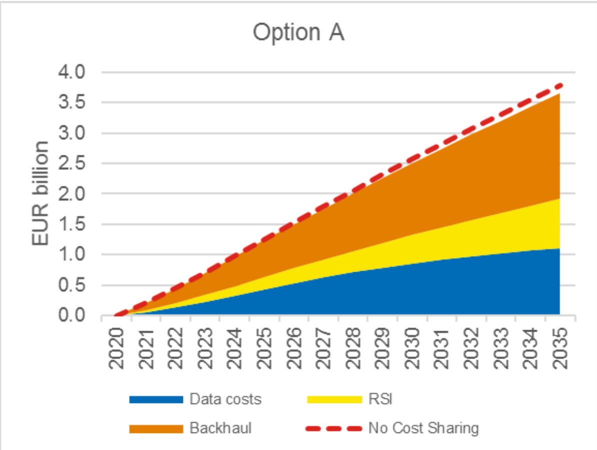


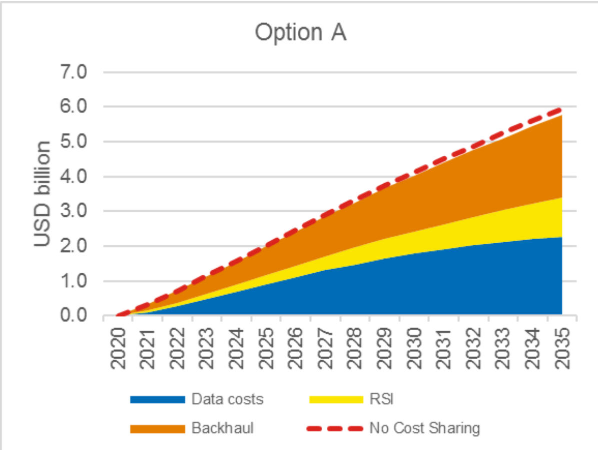
Total cumulative costs

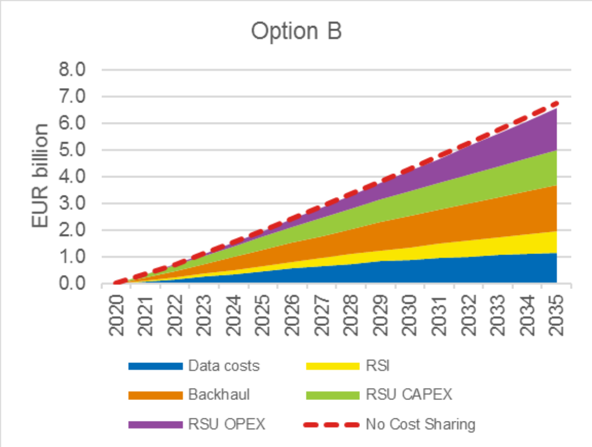




Breakdown of cumulative cost per option






Option B
EUR billion
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
2020
2021
2022
2023
2024
2025
2026
2027
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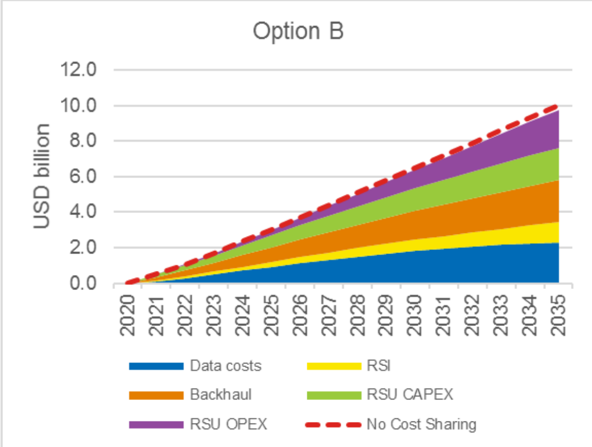
2031
2032
2033
2034
2035
Data costs
RSI
Backhaul
RSU CAPEX
RSU OPEX
No Cost Sharing


Option B
USD billion
12.0
10.0
8.0
6.0
4.0
2.0
0.0
2020
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2024
2025
2026
2027
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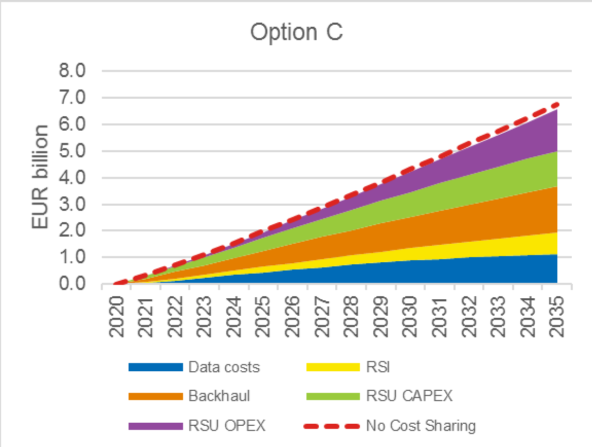
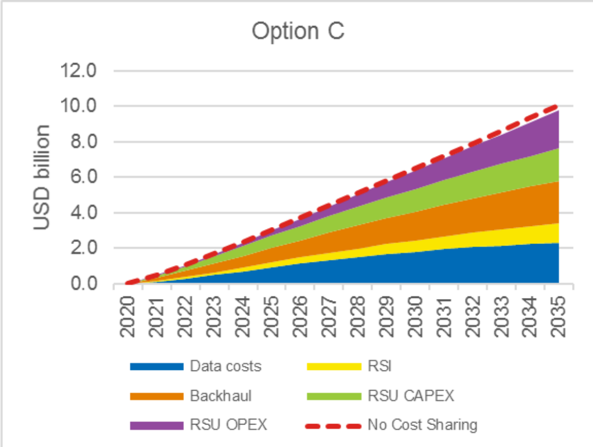
2032
2033
2034
2035
Data costs
RSI
Backhaul
RSU CAPEX
RSU OPEX
No Cost Sharing


Option C
EUR billion
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
Data costs
RSI
Backhaul
RSU CAPEX
RSU OPEX
No Cost Sharing


Option C
USD billion
12.0
10.0
8.0
6.0
4.0
2.0
0.0
2020
2021
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2026
2027
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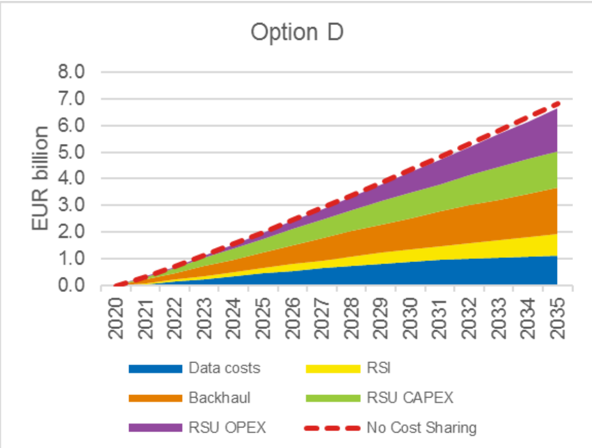
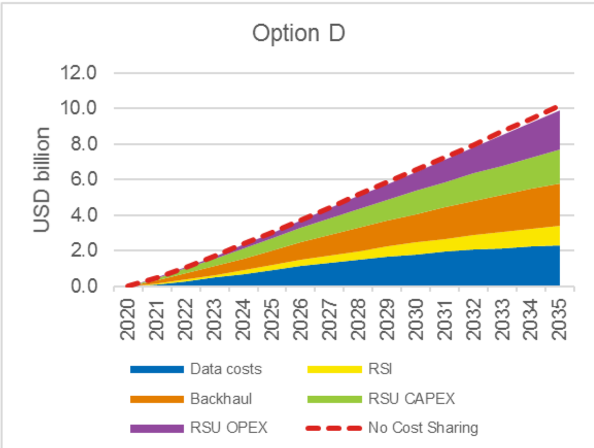
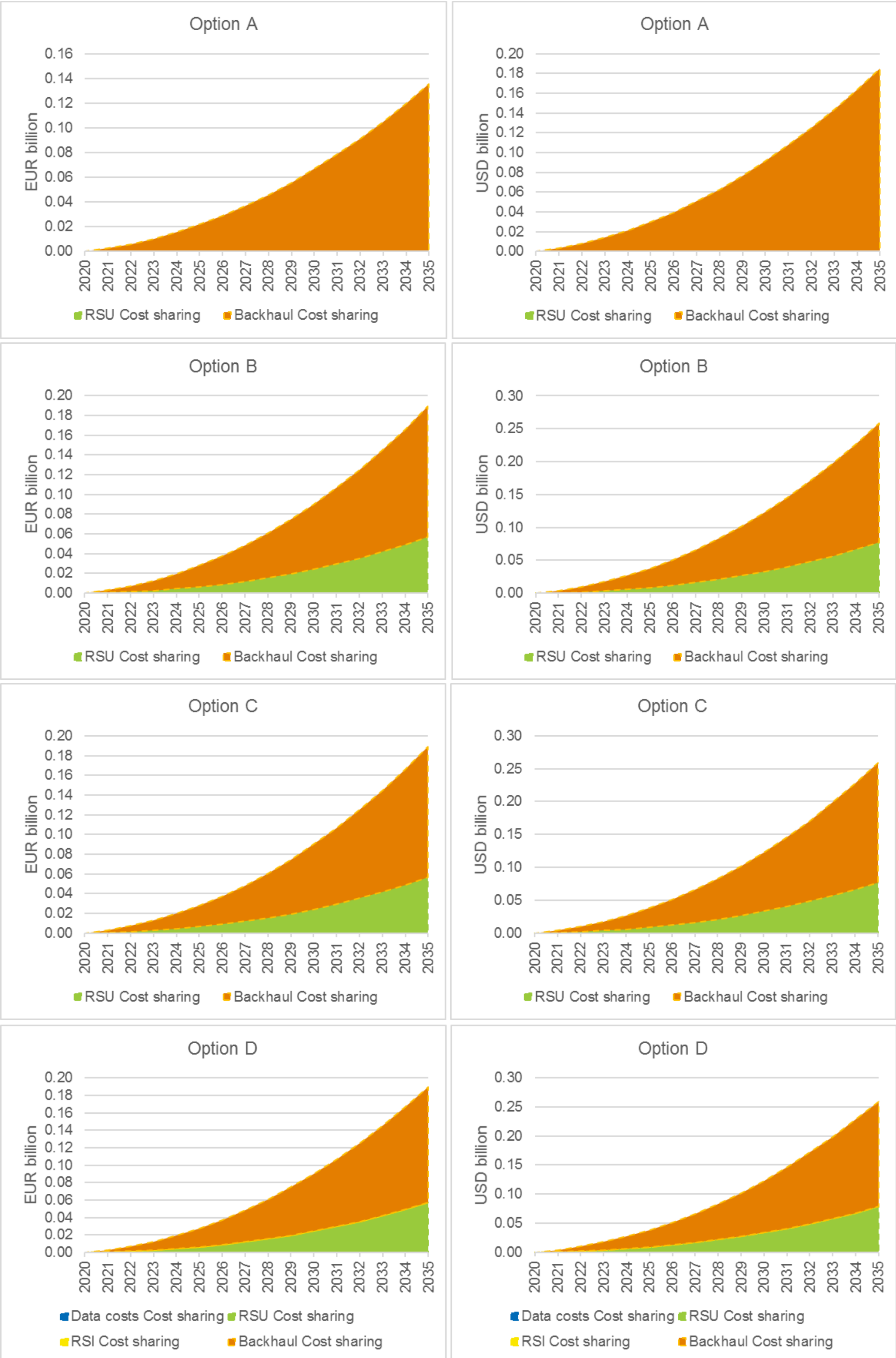
2033
2034
2035
Data costs
RSI
Backhaul
RSU CAPEX
RSU OPEX
No Cost Sharing


Option D
EUR billion
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
Data costs
RSI
Backhaul
RSU CAPEX
RSU OPEX
No Cost Sharing

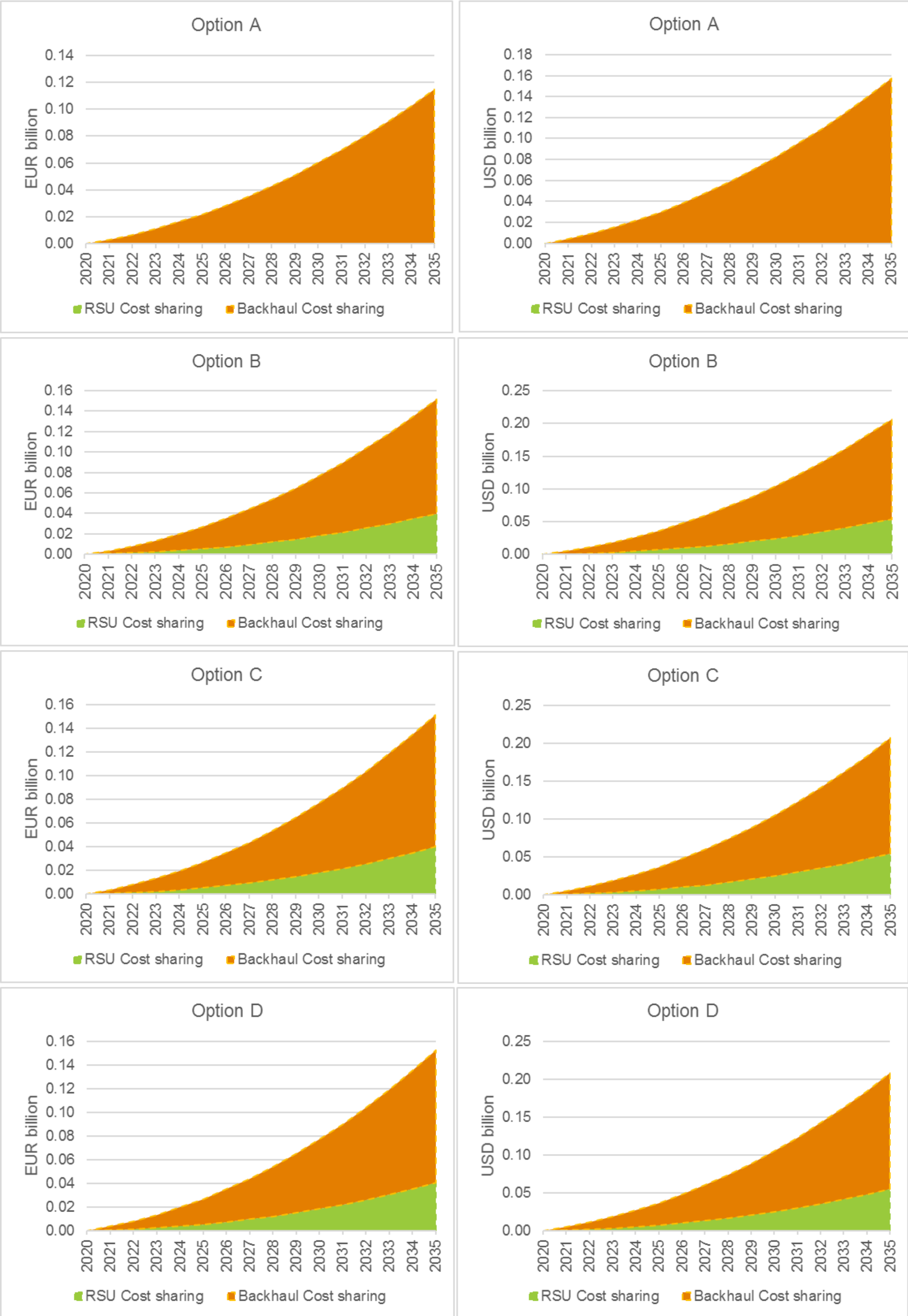

Option D
USD billion
12.0
10.0
8.0
6.0
4.0
2.0
0.0
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
Data costs
RSI
Backhaul
RSU CAPEX
RSU OPEX
No Cost Sharing

Cumulative cost saving per option



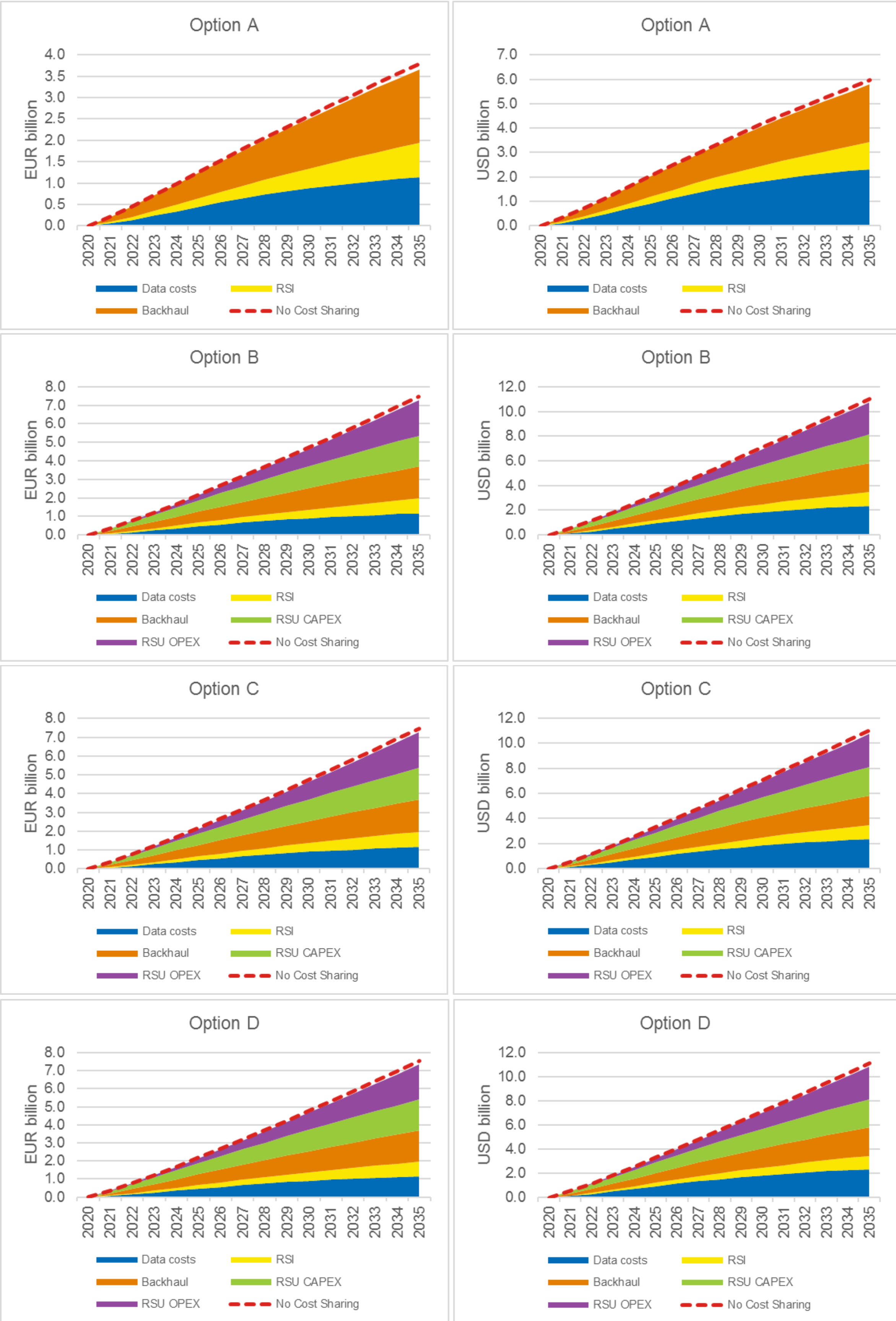
A.2.5.4 Sensitivities

Cost sharing for small cells at 25% urban intersections by 2035

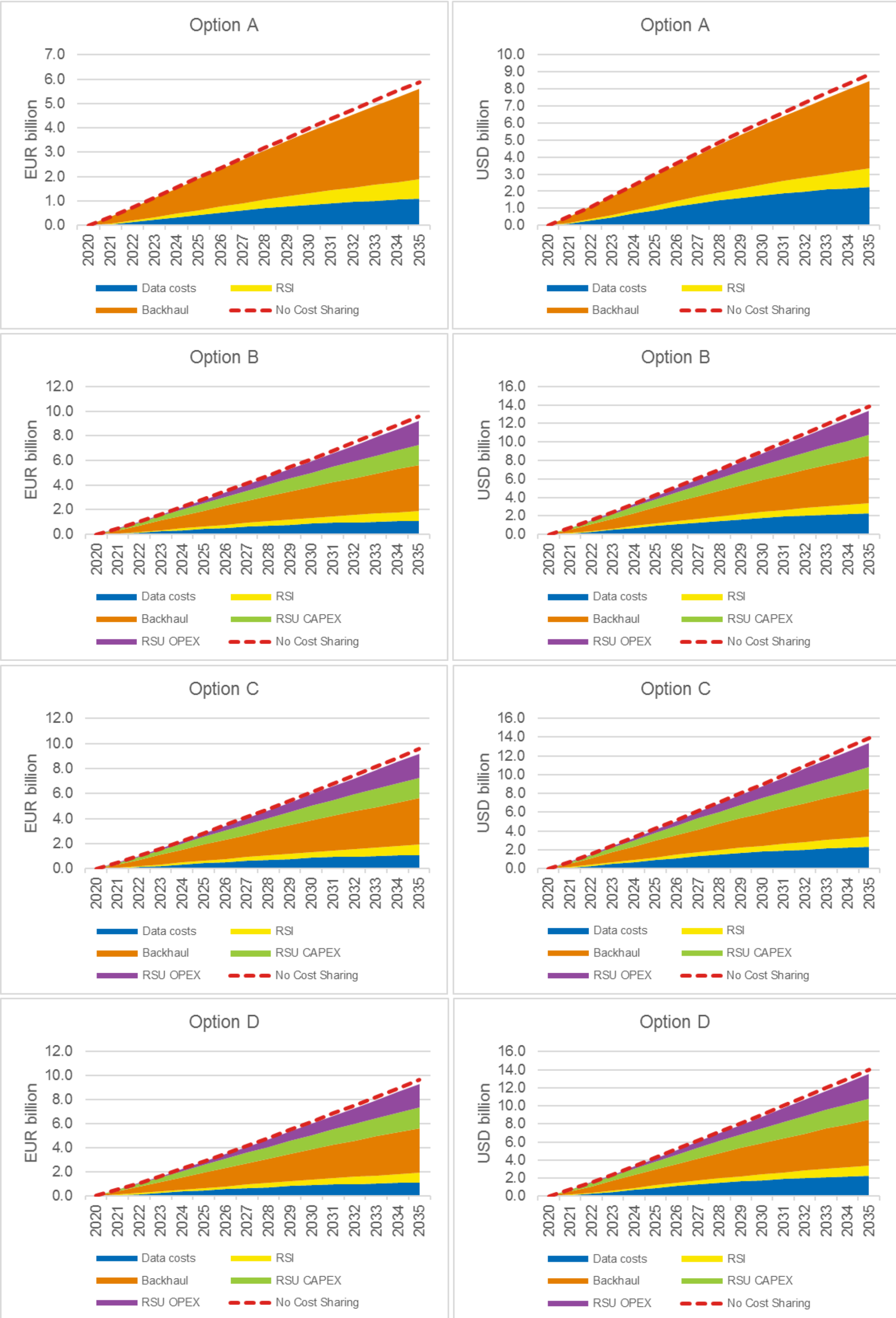


Cost sharing for small cells at 75% urban intersections by 2035

Cumulative Option cost breakdown – new backhaul 25% fibre, 75% cellular



Cumulative Option cost breakdown – new backhaul 75% fibre, 25% cellular

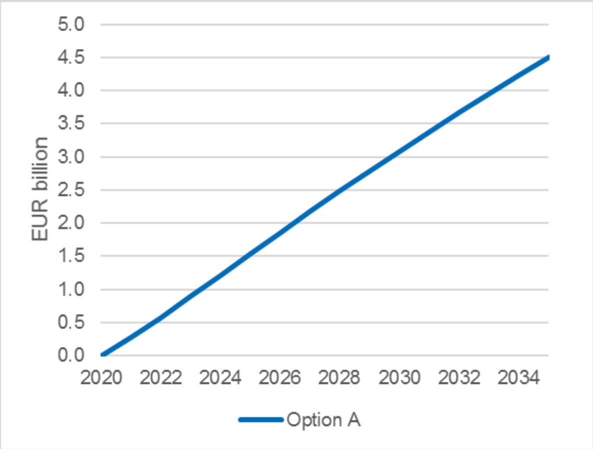


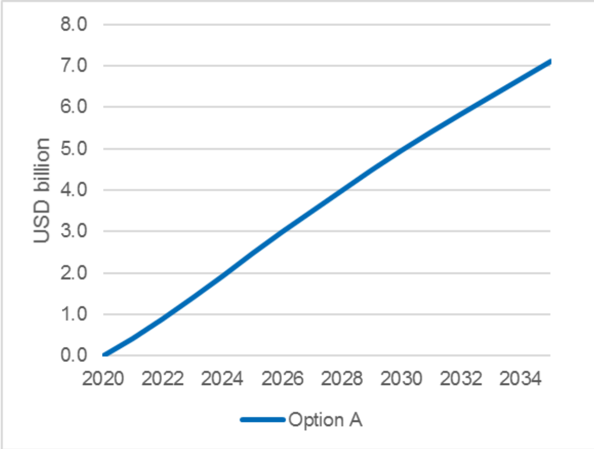
A.2.5.5 Full coverage scenario

As discussed in Section 7, having RSU coverage across the entire road network is unlikely to be practical as millions of RSUs would be required. In the event direct communications coverage was provided to 100% of the road network, a total cumulative cost of EUR70 billion / USD90 billion would be required.

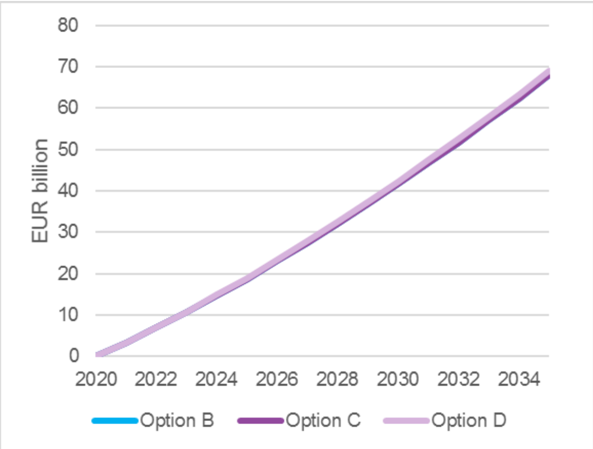
Total cumulative cost

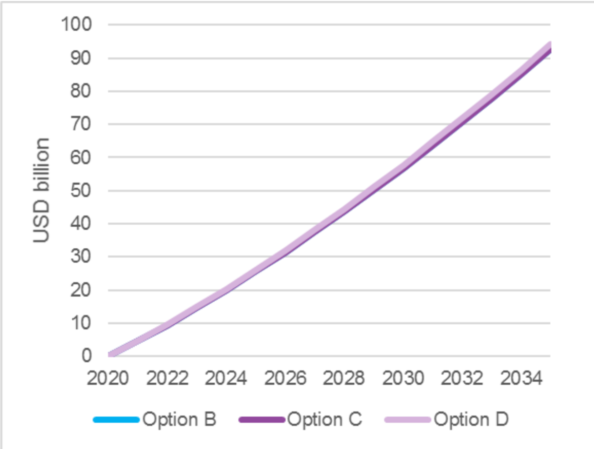
- Option A





- Option B, C and D

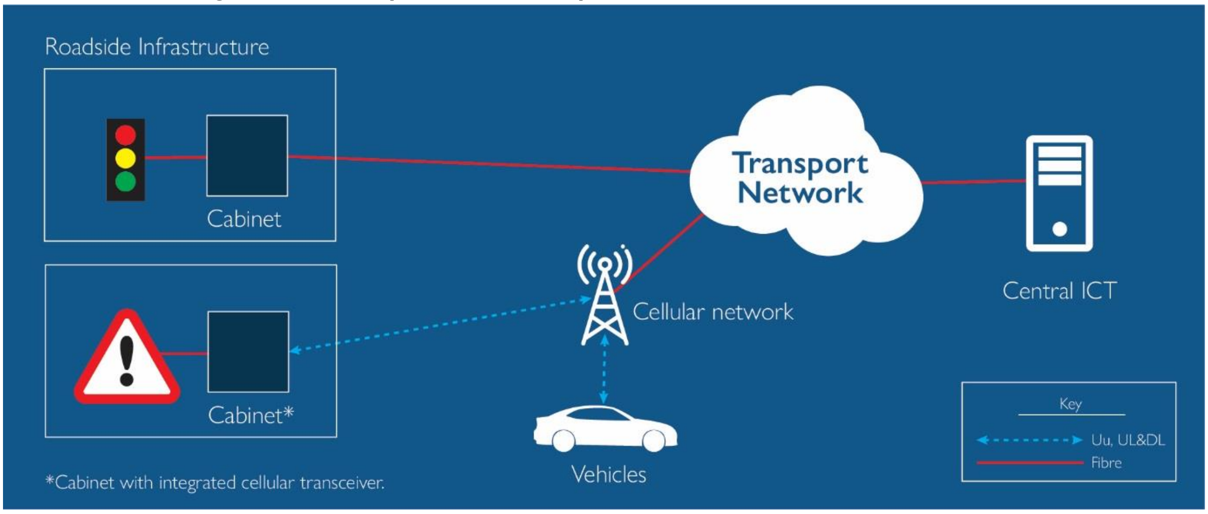




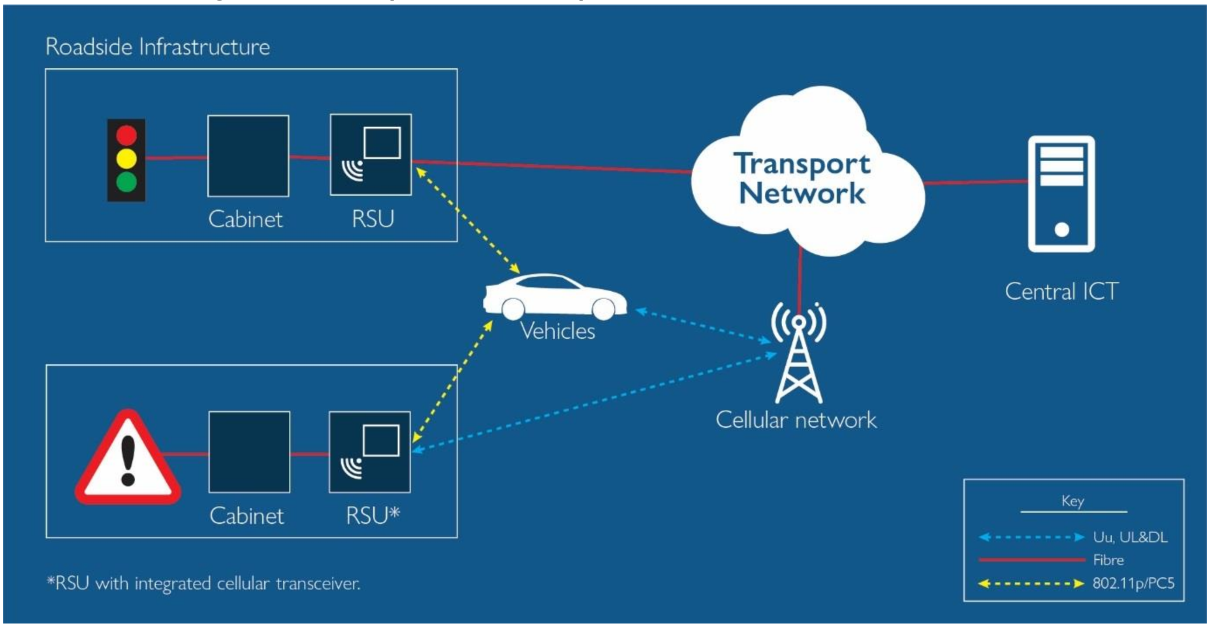
A.3 Annex 3 – Deployment options: additional content

A.3.1 Architectures

Schematic showing the main components in the Option A architecture



Schematic showing the main components in the Option B, C and D architecture



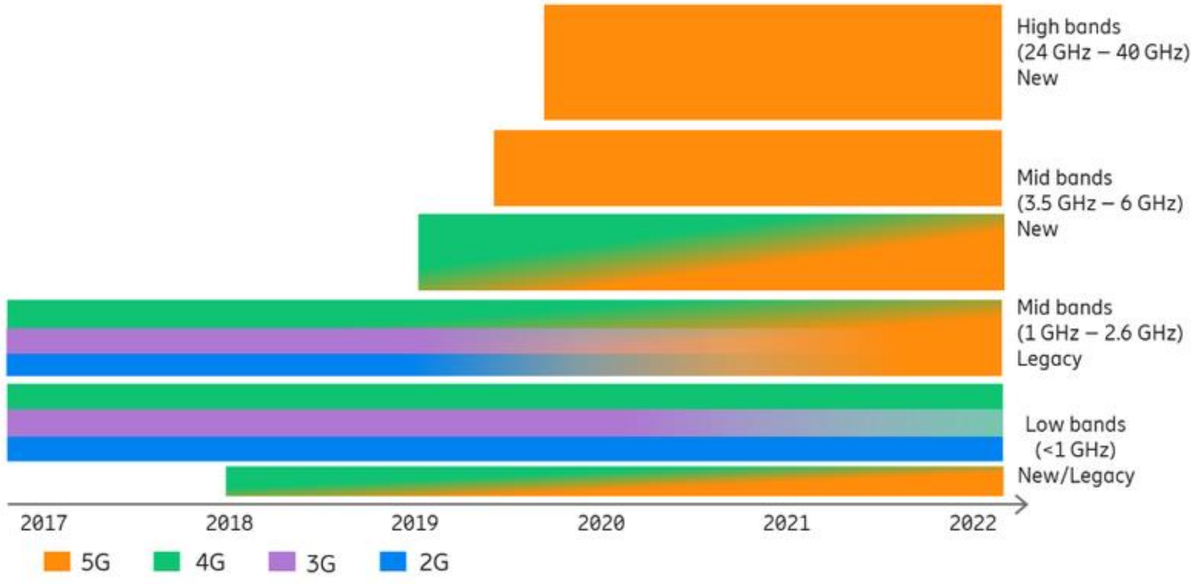
A.3.2 NR

In the short term, cellular connectivity is expected to be provided over LTE-Uu. In the medium to long term, V2I services delivered over cellular will transition to NR-Uu as 5G infrastructure is rolled out. In Europe, the 5G Action Plan aims for all urban areas and major terrestrial transport paths (Motorways and national roads) to have uninterrupted 5G coverage by 2025. In the US, T-Mobile reportedly expect coverage to reach 90% of the USA by 2024[22]. Within this study, 5G relates to sub 6GHz frequency ('low' and 'mid' wireless bands or Frequency Range 1) operation using the 5G-NR standard. It is

[22] European Parliament, *State of Play in Europe, USA and Asia.* 2019.

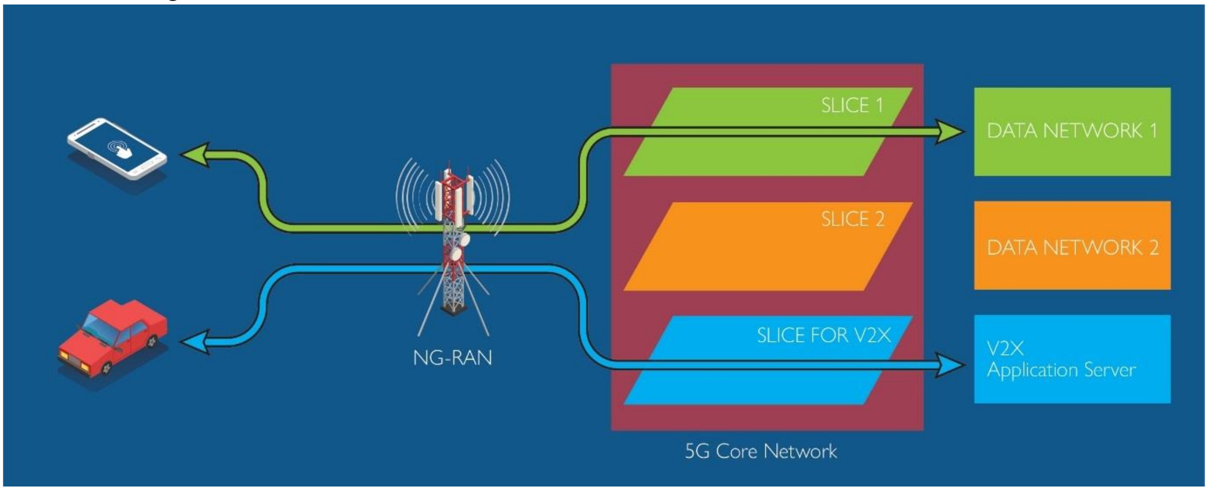
recognised that millimetre wave 5G (mmWave) offers even greater data rate and capacity, however it is outside of the scope of this study.

Expected 5G penetration across the wireless bands (Source: Ericsson)



Network Slicing is a technology that allows multiple logical networks to be created on top of a common shared physical infrastructure. An example commonly cited is the sharing of a given physical network to simultaneously run Internet of Things (IoT), enhanced Mobile Broadband (eMBB), and very low-latency (e.g. vehicular communications) applications, each assigned a different network slice. As each slice is logically separated from the others, it is possible to optimise each one to better support a specific service type. Network slicing can open up new business models, with the network operator being able to partition its network into slices which can then be leased to interested parties. In the case of V2X, the service provider could be allocated a network slice by the network operator, making it easier to guarantee the capacity and the Quality of Service (QoS) requirements to V2X. Network slicing is possible in LTE[23], but it is less easy to implement and less flexible than in NR, where the architecture has been designed to natively support slicing; it may also require a network upgrade.

Network slicing



To further increase reliability of cellular communications, the concept of Predictive QoS is being developed by industry. Predictive QoS will address circumstances in which a rapid change in QoS can have adverse effects on some automotive applications. It will provide notifications in advance of

[23] Some features such as CUPS (Control and User Plane Separation), APN (Access Point Names) and DECOR (Dedicated Core) / eDECOR (enhanced Dedicated Core) make it possible for LTE networks to handle advanced tasks like network slicing.

possible QoS changes to ensure that applications have sufficient time to adapt their behaviour before the change occurs[24].

A.3.3 MEC

One technology that will be beneficial in this scenario is Mobile Edge Computing (MEC), which aims to move the content and processing closer to the end user. The main effect will be a reduction in latency, by locating applications close to where the data is generated or consumed and reducing traffic in the backhaul. This will be very useful for vehicular networks, which are highly dynamic environments. For example, real-time traffic data could be stored and processed locally, eliminating the delay that would otherwise be required to transmit the data to a centralised server. It is worth noting that having computing at the edge could have implications for security, which will need to be taken into account by the network operator or the roadside operator and may have an impact on the system costs.

Evidence suggests that road operators are aware of the potential benefits of MEC but are yet to consider it in a significant way to support V2I services. The technology and business models around MEC are still being developed, and it is questioned whether it represents a major benefit or differentiator to delivering V2I services. MEC can support ultra-low latency and improved reliability, which may be features that are more applicable to V2V services and higher levels of automation, such as platooning, emergency brake light warning and teleoperated driving. V2X is just one part of the MEC business case, and other use cases, such as AR/VR and infotainment may be more significant.
A challenge that has been raised by network operators is multi-operator MEC, which could lead to interoperability issues and service fragmentation. A single infrastructure common to multiple operators could promote integration and harmonisation of services and reduce the deployment cost for the operators, resulting in faster acceptance. GSMA are working to address this by creating an open platform and establishing a multi operator forum[25].

[24] L13 5GAA 2020 Making 5G Proactive and Predictive for the Automotive Industry
[25] https://www.gsma.com/newsroom/press-release/telecom-operators-collaborate-to-build-the-telco-edge-cloud-platform-with-gsma-support/

A.4 Annex 4 – Enhanced V2X services

The table lists additional enhanced V2X (eV2X) use cases defined by 3GPP and enabled as part of Release 15 and 16. They include both safety and non-safety uses cases. Please refer to the specification for a description of each case.

Use Case
eV2X support for vehicle platooning
Information exchange within platoon
Automotive: sensor and state map sharing
eV2X support for remote driving
Automated cooperative driving for short distance grouping
Collective perception of environment2
Communication between vehicles of different GPP RATs
Multi-PLMN environment2
Cooperative collision avoidance (CoCA) of connected automated vehicles
Information sharing for partial/ conditional automated driving
Information sharing for high/full automated driving
Information sharing for partial/ conditional automated platooning
Information sharing for high/full automated platooning
Dynamic ride sharing
Use case on multi-RAT
Video data sharing for assisted and improved automated driving (VaD)
Changing driving-mode
Tethering via Vehicle
Use case out of G coverage
Emergency trajectory alignment
Teleoperated support (TeSo)
Intersection safety information provisioning for urban driving2
Cooperative lane change (CLC) of automated vehicles
Proposal for secure software update for electronic control unit
D video composition for V2X scenario
QoS aspect of vehicles platooning
Adjustment of gaps for platooning
QoS aspects of advanced driving
Assistance to automated driving
Authorization to support automated driving
Notification of updated information to support automated driving
Support for adjustment and big data transport
Support of automated driving in multi-PLMN environments
Reliable and guaranteed connectivity service
QoS aspect of remote driving
Notification of QoS change for remote driving application
Support of remote Driving
Disengagement of autonomous driving
Provision of freedom of mobility
QoS Aspect for extended sensor
Different QoS estimation for different V2X applications

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