C-ITS Vehicle to Infrastructure Services: how C-V2X technology completely changes the cost equation for road operators

White Paper

Contents

1. Executive Summary 4
2. Introduction 5
  2.1 Definitions 6
  2.2 V2I ITS Services 6
  2.3 Relationship to V2V and V2N2V services 7
  2.4 Status of available C-ITS services 8
    2.4.1 Interworking between services and vehicles carrying V2N2I services 10
3. Considered deployment options 12
4.Technical and deployment considerations for different solutions 13
  4.1 Existing cellular network infrastructure for delivering services via V2N2I communications 13
  4.2 Dedicated RSU-based V2I infrastructure 14
  4.3 Road infrastructure upgrades 15
5. Deployment (CAPEX), Operation and maintenance (OPEX), and communication costs 16
  5.1 CAPEX: Infrastructure deployment costs 16
    5.1.1 Existing cellular networks deployment cost 16
    5.1.2 RSU deployment cost 16
  5.2 OPEX: Operation and maintenance costs 16
    5.2.1 Cellular networks operation and maintenance costs 16
    5.2.2 RSU operation and maintenance costs 17
  5.3 Connectivity cost 17
    5.3.1 Cellular networks connectivity cost 17
    5.3.2 RSU connectivity cost 17
  5.4 Leveraging on existing cellular networks and complementary RSUs 17
6. Business comparison summary 18
  6.1 Regional analysis 18
  6.2 Intersection-based analysis in a city 19
7. Conclusions 20
  References 20
Annex A: Scope and Limitations 23
  A.1 Application requirements for transmissions 23
  A.2 Combined cellular networks and RSU 23
  A.3 Road infrastructure upgrades for existing cellular networks and RSUs 23
    A.3.1 Cellular based architectural approach with local processor units 24
    A.3.2 Cellular based architectural approach with controllers' upgrade 25

A.3.3 RSU based architectural approach with optional cellular backhaul link.............................. 26
A.4 Further considerations.. 27
Annex B: Study cases.. 28
B.1 Region wide analysis in Great Britain.. 28
B.2 Intersection-based analysis in the city of Coventry 28
Annex C: Modeling of cellular-based V2N2I.. 30
Annex D: Modeling of RSU-based V2I 32

1. Executive Summary

C-ITS decision making is often obfuscated by technicalities and selective arguments, distracting from the real goal of accelerated and widespread uptake of C-ITS in vehicles and in road network ITS systems in order to prevent millions of road deaths and injuries each year; to enrich the economic fabric of countries by enabling better journeys; and to optimize the use of existing and future expensive road network infrastructure physical assets. To that end, government road strategists, planners and operational managers need to objectively consider the best ways to accomplish a rapid uptake of high quality and affordable C-ITS solutions. Leveraging existing 4G LTE and future 5G mobile networks is a certain way to save Billions of Euros / Dollars over time, while acquiring high performance, highly reliable, highly secure solutions with a future development roadmap aligned to the world's biggest single technology ecosystem.

The cost of delivering ITS services with existing cellular networks is significantly lower compared to widespread RSU rollout: in the best cases, it could be even more than a hundred times lower than with only dedicated RSUs.

In this White Paper, the 5GAA provides analysis on the benefits of using existing cellular networks for the delivery of Cooperative Intelligent Transport Systems (C-ITS) services, in combination with dedicated RSU deployment. The analysis describes deployment options in terms of expenditures over a ten-year timeframe for the deployment of ITS services for vehicles communicating with infrastructure. For each option, the deployment costs, operation and maintenance cost, and connectivity costs are analyzed.

The analysis highlights complementarity between cellular long-range technologies, i.e., mobile networks, using the cellular (Uu) interface and sidelink (PC5) technologies. The motivation to leverage existing cellular networks is clear, given the fact that in many parts of the world, traffic signal status, variable road signs etc., are already digitally connected and centrally managed, in some cases with public internet interfaces already developed.

The business and technical implications of these analyses are scenario-dependent. We therefore split the analysis for different road types (Motorway, Urban A roads, Urban minor roads, Rural A roads, Rural minor roads) and for an intersection-based analysis, to show the impact in a variety of different settings.

Regardless of the technology choices, there are upgrades required for traffic management and road infrastructure. The solutions and associated costs are varied and largely depend on pre-existing conditions and available infrastructure in different regions or cities. In certain cases, traffic Signal Phase and Timing (SPaT) information is already accessible via an open interface with the traffic manager. In other cases, additional upgrades are required.

The results show that the public cost of delivering ITS services with existing cellular networks is significantly lower compared to widespread RSU rollout. On secondary road networks, it could be even lead to a hundred-fold saving compared to dedicated RSUs deployment. Therefore, 5GAA encourages Road Authorities to evaluate alternative ways to deliver C-ITS V2I priority services and contemplate leveraging existing cellular networks to substantially reduce implementation and delivery costs.

This paper approaches the topic by:

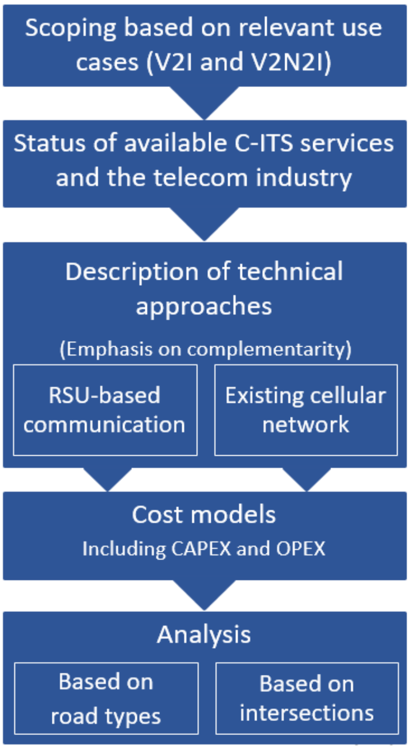
- Defining the scope of services that can be reasonably delivered over cellular networks, and which services depend on road side units;

- Explaining the state of the industry, and highlighting examples where infrastructure services are already being provided over cellular networks today, as well as the architectural and technical considerations that are important to delivery of these services, such as spectrum, coverage, multi-operator and roaming agreements;

- Detailing two different technical approaches: either build-out of dedicated RSU-based communication V2I infrastructure (C-V2X PC5 or 802.11p based ITS-G5/DSRC), or a mix of RSU and cellular based deployment. Special consideration is given to the state of traffic signal infrastructure, and that in some cases it may not be possible to leverage cellular networks immediately;

- Explaining the cost models for these different approaches, including the capital (CAPEX) and operational (OPEX) considerations that are important for road operators;

- Finally, these different models are applied to a variety of road scenarios to clearly show that there is a very real benefit to taxpayers if authorities can adopt an approach of delivering ITS services with existing cellular networks – to the extent that without this approach, it may not be reasonable to deploy V2I services in some areas at all.



2. Introduction

Mobile networks and cellular coverage are constantly being evolved and enhanced. Mobile networks support a wide range of services that are beneficial for society and industries today. Delivered services span from Automotive Infotainment, remote tele-working and ordinary voice calls to ITS Services such as improved safety, traffic efficiency, autonomous driving enabling services, Mobility as a Service (MaaS), improved logistics, efficient road maintenance and operations and automatic crash notification (ACN) as legislated by eCall.

Infrastructure C-ITS services can be delivered as V2I with short range radio, V2N2I with cellular networks, or a mix of both.

The scope of this work is limited to ITS services involving vehicles communicating with the infrastructure[1] which have high societal benefits and the maturity of technology will allow them to be available in the short term. The study considers that such services could be delivered with V2I (Vehicle-to-Infrastructure) direct communication to locally emplaced RSUs, or with V2N2I (Vehicle-to-Network-to-Infrastructure) communication via cellular network connection to more centralized traffic management center interfaces. We will reflect on the services to differentiate those that would be more efficiently delivered on cellular (V2N2I), on RSU (V2I), or using a combination of both solutions. This will highlight the complementarity between cellular long-range technologies, i.e., mobile networks, using the cellular (Uu) interface and sidelink (PC5) technologies. Ultimately, Road traffic Authorities (RTAs) will make

[1] For example, these services fall in the category of "Day 1/1.5" V2I ITS Services by the C-ITS Platform in Europe.

the decision on which type of solution should be adopted in their context and where these solutions should be adopted.

2.1 Definitions

V2I (Vehicle-to-Infrastructure): short range communication where one endpoint is a vehicle and the other endpoint is a roadside infrastructure with an RSU. Messages may be transmitted in both directions between the endpoints.

V2N2I (Vehicle-to-Network-to-Infrastructure): is indirect communication between a vehicle and a roadside infrastructure via the cellular network and ICT infrastructure. The vehicle uses cellular communications through Mobile Network Operator (MNO) licensed spectrum.

V2N2I Service Provider: Obtains messages from Road Operators via API and distributes to registered vehicles/UE/V2N2I clients appropriately (according to location or proxy for location). Can send messages received from V2N2I clients to appropriate Road Operators. V2N2I Service Provider is a special case of V2I Service Provider which uses cellular networks. This role could be taken by a Road Authority, an MNO or OEMs.

Roadside Infrastructure: is road traffic management equipment installed along the roadside, to convey traffic or traveler information to passing drivers. Traffic lights and variable road signs are examples of roadside infrastructure.

RSU (Roadside Unit): is a communication unit, often connected to roadside infrastructure. For the purpose of the analysis, RSU supports V2I communication and communicate with vehicles using short range communication (e.g. C-V2X PC5 or 802.11p). RSUs may be connected to the network through wired or wireless long-range backhaul.

Road Operator (RO): Provides standard messages to V2N2I service provider via APIs. Can receive messages from vehicles/UE/V2N2I clients via V2N2I service provider to inform RO's real-time road information.

2.2 V2I ITS Services

The scope of this white paper is limited to ITS services involving vehicles communicating with the infrastructure which can be delivered using cellular networks or RSUs, in order to show economically beneficial options in terms of expenditures over a ten-year timeframe.

Cellular networks play a fundamental role in economically delivering these types of ITS services. Some examples of the V2I ITS services (which are assumed to include V2I and I2V, as well as V2N2I and I2N2V communications) include [1]: Hazardous location notification, Road works warning, Weather conditions, In-vehicle signage, In-vehicle speed limits, Probe vehicle data, Shockwave damping, Green Light Optimal Speed Advisory (GLOSA) / Time To Green (TTG), Signal violation/Intersection safety, Traffic signal priority request by designated vehicles, Off street parking information, On street parking information and management, Park & Ride information, Information on Alternative Fueled Vehicle (AFV) fueling & charging stations, Traffic information and smart routing, Zone access control for urban areas, Loading zone management, Wrong way driving. Such services are expected to contribute to traffic safety, efficiency, comfort, and the environment, benefitting different parts of society.

Mobile communications have advanced significantly since V2I services were defined by ETSI – some of the architectural principles date from a time when smartphones were still a new concept.

V2I Services should not be confused with V2N (Vehicle-to-Network) Services such as telematics, software/maps download and update, etc., which are typically delivered based on dedicated agreements between the MNO, the OEM, the service provider, and the vehicle owner where applicable. Such V2N Services are not discussed in this document since the scope is only on the C-ITS V2I priority services.

These services were defined by ETSI[2] in a context and time when mobile communications were not as advanced as today. Mobile communications have advanced significantly since then, as elaborated in Section 0; nevertheless, the services can be grouped according to their relevance area as follow:

- Services triggered at specific locations: these services correspond to those that are applicable to areas such as intersections (signalized and unsignalized), merges, exits and any other location where local data should be made available to a vehicle. Representative services include GLOSA/TTG, signal violation/intersection safety, road works warning, etc.
- Services which are executed in wide areas: these services correspond to those where the executing location is not possible to predict, since they may happen anywhere. Representative services include hazardous location notification, shockwave damping, traffic signal priority request by designated vehicles, etc.

It is worth noting that a host of C-ITS V2I priority services can be provided by either long-range technologies (cellular communications using Uu) or short-range communications (using RSUs and PC5), as elaborated upon in Annex A (Section A.1). As general guidance, some services are better served by existing cellular networks while other are expected to be provided mainly over RSUs due to latency requirements. The following services are delay tolerant and are most effectively delivered over cellular communications using Uu (V2N2I):

- Off street parking information.
- On street parking management & information.
- Park & Ride information.
- Information on fueling & charging stations for alternative fuel vehicles.
- Traffic information & Smart routing.

Other services may or may not be delay tolerant. Depending on context and implementation, they may be better delivered using cellular communications over Uu (V2N2I) or delivered over short-range communications over PC5 (V2I). They include:

- Road works warning.
- Weather conditions.
- Other hazardous notifications.
- In-vehicle signage.
- In-vehicle speed limits.
- Traffic signal priority request by designated vehicles.
- Green Light Optimal Speed Advisory (GLOSA).
- Probe vehicle data.

However, some V2I services have in fact lower latency and reliability requirements and would require a short-range communications interface as an integral part of the solution in warning and pre-crash situations, such as signal violation and intersection safety.

2.3 Relationship to V2V and V2N2V services

Safety critical V2V (Vehicle-to-Vehicle) ITS services are expected to be delivered primarily through short range communications technologies. Other safety critical use cases that require guaranteed low latency reliable communications should also be supported by short range communications, including PC5. More delay tolerant services can also be economically delivered over V2N2V; these services are out of scope for this paper, but they will be addressed in an upcoming 5GAA study. In addition, it is important to highlight

[2] ETSI Basic Set of Applications TR 102 638

that services requiring low latency and high reliability could also be provided over Uu (for V2N2V and V2N2I) using future technologies such as 5G and distributed cloud systems.

2.4 Status of available C-ITS services

In many parts of the world, including Europe, traffic signal status, variable road signs etc., are already available on the Internet on commercial terms, e.g., by HERE around the world[3], TSS in the US[4] and 'Talking traffic'[5] in Netherlands. Other ongoing activities to connect traffic lights and provide traffic safety information are the EU financed 'Nordic Way'[6,7] project, the 'Drive Sweden'[8,9] project, and the Telstra and Lexus trial in Australia[10]. To make traffic light information available on Internet for usage is one way to manage investments needed for a Road traffic authority/road operator.

Fundamental parts of the C-ITS ecosystem and related legislation were created over a decade ago when vehicles were not connected at all, had limited sensors installed and where coverage and performance of cellular mobile networks was limited. The contrast with the capability of a modern vehicle and mobile network is extreme, and it is expected that any new regulatory action would reconsider these underlying assumptions to ensure that all investment is spent wisely.

Making traffic light information available on Internet for usage is one way to manage investments needed for a Road traffic authority/road operator, and is already common in many parts of the world.

Mobile network coverage has been a topic of debate regarding C-ITS, with some sources suggesting that current coverage is limited and not sufficient in areas where C-ITS services would take place. Nevertheless, most C-ITS services are relevant on major roads and densely populated areas where cellular coverage exists and there are already many regulatory bodies who publish official data about mobile network coverage and update it in periodic manner. For example, Arcep (the telecommunications regulatory agency in France) provides coverage maps for the whole country [14], showing the expanding coverage in the territory. Moreover, the French Government, Arcep and mobile operators announced a historical agreement to accelerate mobile coverage in the Regions [15] and mobile operators have committed to improve reception quality across the country, particularly in rural areas and, more importantly for C-ITS, there is a commitment to accelerate the coverage of transportation routes, so that all of the major roads and railways have 4G coverage. Orange, SFR and Bouygues Telecom have committed to ensuring a base quality of voice/SMS and superfast mobile (4G) coverage by 2020. This commitment will be written into their existing licenses in 2018.

It is expected that cellular connectivity will be available in 55% of new vehicles globally by 2020, and 5GAA estimates that there are already more than 100 million vehicles today with connectivity capabilities on the road.

In Australia, the government is providing direct funding[11] to improve mobile coverage in regional and remote communities, based on priority targets. Although C-ITS applications are not directly considered in the current selection of locations for improved coverage, this would become an important consideration as usage of connected vehicles, especially for safety applications, increases. Closely related to network coverage aspects is the **penetration rate** of cellular modems in new vehicles. It is expected that cellular connectivity will be available in 55% of new vehicles globally by 2020 and this percentage is expected to be higher in the EU [7] where

[3] https://www.here.com/en/company/newsroom/press-releases/2016-26-09
[4] https://www.traffictechservices.com/how-it-works.html
[5] https://www.ericsson.com/en/cases/2017/smart-talking-traffic-ecosystem
[6] http://vejdirektoratet.dk/EN/roadsector/Nordicway/NordicWay1/Pages/Default.aspx
[7] https://itsworldcongress.com/demonstrations/demonstrations-in-copenhagen/nordic-way-2/
[8] http://www.swarco.fi/Uutiset/Uutiset/Ajankohtaiset/SWARCO-%E2%80%93-the-hub-for-connected-traffic
[9] https://www.drivesweden.net/sites/default/files/content/bilder/connected_traffic_signals_-_johan_ostling.pdf
[10] https://exchange.telstra.com.au/australian-first-lexus-connected-vehicle-trial-set-to-make-roads-safer/
[11] https://www.communications.gov.au/what-we-do/phone/mobile-services-and-coverage/mobile-black-spot-program

consumers demand connected cars, and legislation for automatic crash notification (ACN) is required by legislation in new vehicles from 2018. 5GAA estimates that there are more than 100 million vehicles with connectivity capabilities on the road. This is particularly relevant since certain capabilities related to C-ITS services can be achieved via software update for vehicles equipped with modems that support cellular communication. On the infrastructure side, the main limiting factor are the barriers perceived by authorities due to high cost to connect traffic signals to central networks, which is a similar barrier regardless of the technical solution.

Another assumption is the required mobile operator subscription, suggesting that it could be a negative point to use commercial mobile networks due to the subscription model. However, this should not be a concern since mobile operators have adapted in recent years to new types of contractual agreements that are adapted to the lifetime of the vehicle (as it is done in the case of eCall) or electricity meters (as in done with smart meters in several EU member states). This is only required for the cellular connection of course: C-V2X technologies also comprise short-range communications in the 5.9 GHz ITS spectrum band, which like 802.11p based technologies, do not require network coverage or subscription.

A common concern is the latency performance when utilizing cellular networks in combination with cloud or centralized solutions to relay data between cars and infrastructure. However, this is a practical solution in the context of the C-ITS V2I priority services and can provide satisfactory performance for the majority of use-cases. It is worth noting that the C-V2X architecture – Uu and PC5 – addresses all of the services and offers flexibility with choice of network. Furthermore, support for Quality of Service (QoS) is a standardized, existing functionality in mobile networks, meaning that C-ITS traffic can be prioritized and receive the required latency, so C-ITS information can be delivered even if the mobile network is heavily loaded; this type of prioritization is already done today based on commercial agreements. For instance, voice calls on 4G (VoLTE) have specific handling to ensure high quality audio and being able to handle a wide variety of different services with appropriate performance and quality is one of the key components of future 5G networks. There are other technical issues that may need addressing, such as connectivity interruptions when changing mobile network. However, this can already be technically addressed by mobile network configurations which have not been widely used between different mobile networks so far. Several ongoing projects are currently working in this area, as further elaborated in Chapter 0.

Related to subscription costs is the issue of acquiring spectrum licenses, which is sometimes considered a disadvantage, but can also be a mechanism to foster mobile network coverage expansion. This has been tried in the Digital Dividend spectrum auctioning process in Germany, in the way the network build-out was required in the scope of attached spectrum licenses. MNOs that were successful in bidding for the 4G spectrum had to build out in rural areas first, before starting to use the spectrum for capacity improvements in urban areas [16]. Recently, Members of the European Parliament made a call to the European Commission, local authorities, and Member States to provide proper funding to upgrade and maintain the future road infrastructure [17].

Spectrum licensing can be a mechanism to foster mobile network coverage expansion, for instance, rural or other underserved areas. In future, this could be used to accelerate coverage of roads and highways, too.

5GAA has developed System Profiles of Cellular-V2X consisting of both Uu network-based and PC5 direct communications interfaces for the deployment of C-ITS services. The communication system profile of cellular Uu and PC5 interfaces specifies configuration of existing ITS standards and provides implementation options ensuring interoperability of C-ITS services based on mobile cellular networks. 5GAA have shared the Cellular-V2X system profiles with the C-Roads platform and other European C-ITS projects for a harmonized development of C-ITS services.

Finally, in the next section, the concerns related to mobile operators interworking are presented in detail.

2.4.1 Interworking between services and vehicles carrying V2N2I services

The role of the Mobile Network Operator (MNO) in V2N2I is to provide a message distribution service to the RO with optimized delivery of messages and a specific SLA towards the RO[12]. With V2N2I services the following potential scenarios might arise:

- Vehicles in mutual proximity are connected by different mobile networks, supporting V2N2I[13]
- Locations where subscriber's default MNO does not have mobile coverage
- Inter-Road Operator handoff
- International roaming

Below we look at various scenarios where interconnect or other solutions are required.

Vehicles near to each other are connected by different mobile networks, supporting V2N2I

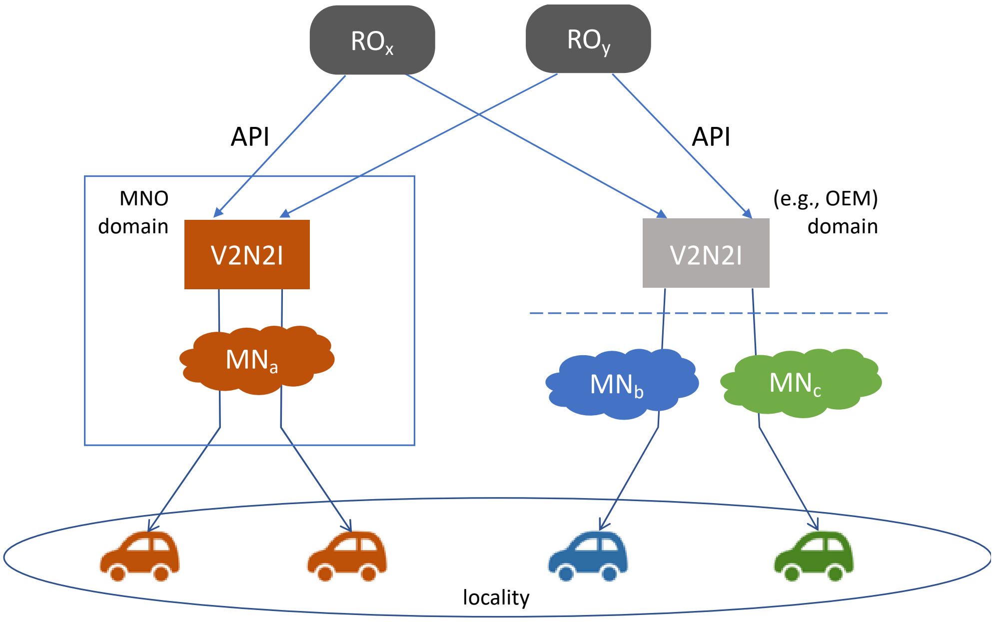


Figure 1: Vehicles connected by different mobile networks supporting V2N2I.

In this scenario the infrastructure of a RO sends a message to be received by all vehicles in a specified geographic area. The vehicles are all connected via mobile networks, but by multiple different mobile networks. Figure 1 shows a scheme for this scenario, where V2N2I service providers could be within the MNOs domain or supported by other actors, for instance by OEMs providing services to their vehicles.

All connected vehicles in the area will be able to receive the same messages originating from the RO, even if they are supported by different V2N2I service providers or MNOs, based on the same set of APIs from the RO.

The vehicles subscribe to a messaging/message forwarding service provided by their MNO or other provider (for example, a common case is for OEMs to take this role). The RO sends a message to each OEM/MNO (via a published API) which is delivered to each vehicle, based on vehicle location or some proxy for location. The solutions for delivering messages to appropriate vehicles is not considered in this section: the MNO or OEM backends can be seen as a 'black box' as far as the RO is concerned.

[12] In the case that the V2N2I service provider is an OEM, an SLA would need to extend from the MNO through the OEM towards the RO – this is more complex than a direct SLA between the MNO and the RO.

[13] By 'supporting V2N2I' we mean that the OEM/MNO service gets and receives each message intended for road users from the Road Operator(s) and distributes the message to appropriate vehicle/UE based on the vehicle/UE location (or some proxy for location).

Locations where the mobile network does not have coverage

There are locations where a vehicle temporarily moves outside the coverage of their mobile network, but a service is available from another mobile network. Since ROs require that V2N2I messages must be received in a timely manner by all vehicles in this area, the vehicle/UE should connect to the V2N2I service via the available mobile network. Figure 2 shows a possible architecture in locations where subscriber's mobile network does not have coverage. To support V2N2I services, vehicles outside their own mobile network coverage roam to available mobile networks and keep their data connection.

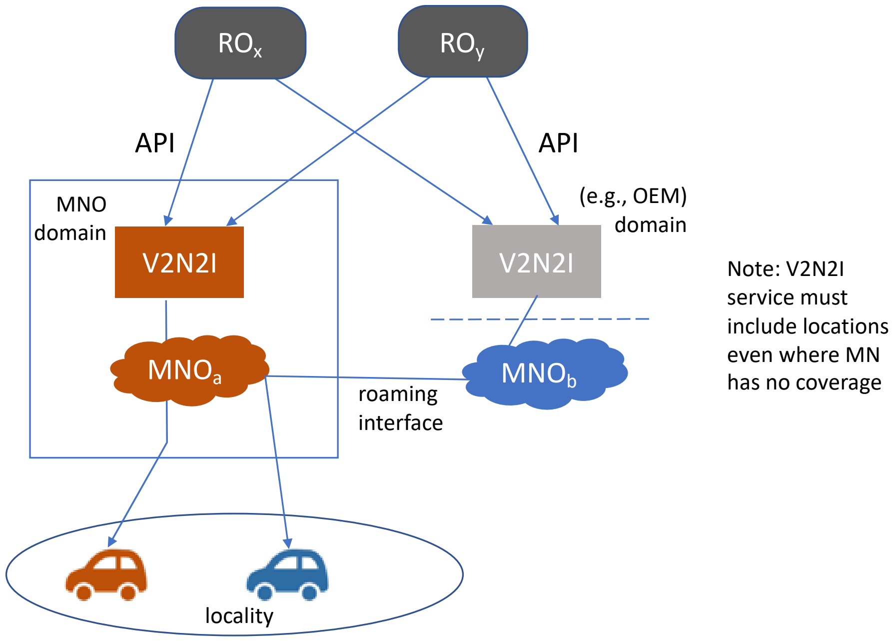


Figure 2: Service support in locations where subscriber's mobile network does not have coverage.

In most IoT services today, roaming to multiple mobile networks is commonly supported. One way of network roaming follows the Home Network model, where communications is routed via the core network of the home subscription. In this case we expect the vehicle to continue service as normal over the roaming interface[14], with the V2N2I service hosted by the home MNO ensuring it supports V2N2I while roaming.

Inter-Road Operator handoff

As shown in Figure 1, the V2N2I service acts as a broker for multiple ROs so the V2N2I service will receive and distribute messages from ROs, according to the current locations of vehicles. The vehicles may be unaware of which RO they are receiving information from, and it is possible that a vehicle can be receiving information from more than one RO at any time, e.g. if a highway passes through a city where the highway is managed by RO 'x' and the surrounding city roads are managed by RO 'y', provided both operators expose relevant information with APIs.

In this case the V2N2I service receives messages from the all of appropriate local ROs and distributes them appropriately to vehicles. No inter-RO 'handoff' is foreseen, from the perspective of the vehicle with this approach.

Inter MNO handoff service outage and 'International' roaming

When a vehicle moves from one MNO's coverage into another, either within a single territory or across a national border, mobile operators must ensure a minimal service outage during handoff. Moreover, if the vehicle roams to another territory, international roaming as per normal roaming agreements will apply. Similar to the above scenario, we expect that 'home network' service routing will occur. In order to provide

[14] Architectures exist to support roaming QoS; however, roaming scenarios are not expected to be included in an SLA between MNO & RO.

a roaming V2N2I service the V2N2I application will need to obtain real-time RO road information from the appropriate 'foreign' RO. The V2N2I message distribution service must also be supported in the visited territory.

One issue that may arise here might be increased latencies due to both accessing RO real-time information over long distances by the MNO 'home network' and then distribution of the message to the vehicle from the home network to the visited network. The achievable minimal service outage and latency performance of V2N2I when roaming abroad are subjects for further study already recognized and discussed by 5GAA.

3. Considered deployment options

The technical and business analysis in this White Paper focuses on two separate technical options:

- Existing cellular network infrastructure for delivering services via V2N2I communications.
- Dedicated RSU-based communication V2I infrastructure (C-V2X PC5 or 802.11p based ITS-G5/DSRC).

In most cases, realistic deployments will entail a mixture of cellular network infrastructure and additional support via RSU-based V2I infrastructure.

Even though improved RSU performance (coverage and reliability) is expected with PC5 compared to 802.11p, the cost for these technologies is similar [10], and they are thus analyzed jointly under the generic "RSU-based V2I infrastructure" label. One possible solution (discussed in Annex A, Section A.2) is based on the combination of C-V2X PC5 RSU functionality embedded alongside small-cell cellular network infrastructure which might be rolled out for future 4G and 5G networks, therefore capturing synergy between two such devices that could offer a win-win scenario in a public-private partnership. Several 5GAA members are engaged in such solution offerings.

The distribution of CAPEX/OPEX are different in the various cases and they are assessed in the rest of the white paper as shown in Table 1. For practical reasons this white paper focuses on Great Britain, thanks to largely available detailed public data [2][3]. Nevertheless, the outcome applies to most European States, and may also be relevant globally. Though certain OPEX may be capitalized, and some CAPEX could be operationalized in terms of expenses, this paper does not look into how the dial can be adjusted to deliver the desired CAPEX/OPEX balance for ROs.

Business and technical implications are scenario-dependent. We therefore split the analysis for different road types (Motorway, Urban A roads, Urban minor roads, Rural A roads, Rural minor roads), according to the classification in [2].

For each technical option, the following costs are analyzed:

- Deployment costs: capital expenditure for network assets and infrastructure.
- Operation and maintenance costs: yearly expenses to operate and maintain the network infrastructure.
- Connectivity costs: correspond to fees related to connectivity services, considered when the service provider does not own and operate the network where the service is provided.

Whichever technology is used to relay information from the infrastructure to vehicles, there are upgrades required for traffic management and road infrastructure. The solutions and associated costs are varied and largely depend on pre-existing conditions and available infrastructure in different regions or cities. In certain cases, traffic Signal Phase and Timing (SPaT) information is already accessible via the Internet. In other cases, additional upgrades are required, and these costs may be similar if RSUs or cellular network connectivity are used to reach the vehicles, as elaborated in Annex A (Section A.3). These alternatives and associated costs will be a subject of further study within 5GAA but are excluded from the scope of this white paper.

A comparative summary is given in Table 1, indicating the section in the document which provide more detail. The study cases are presented in Annex B.

Table 1: Cost split for the considered deployment options

	Deployment costs (CAPEX)	Operation and maintenance costs (OPEX)	Connectivity costs
Existing cellular network infrastructure for delivering V2N2I	• Network deployment costs are the responsibility of MNOs (the cost for service providers are reflected in the connectivity fee) • Existing cellular networks are capable to satisfy the demand to communicate with vehicles for several V2N2I services (Refer to Section 4.1.1) • Possible costs for road infrastructure upgrades (such as local processing units) are out of scope for the cost analyses (but alternatives are described in Annex A.3.1 and A.3.2)	• Network costs are covered by MNOs (these costs are reflected in the subscription fees for connectivity) • Opportunities for cost support by V2N2I service providers are mentioned but not explored in the WP (Refer to Section 0) • Possible costs for new road infrastructure components are out of scope for the cost analyses (but alternatives are described in Annex A.3.1 and A.3.2)	• Subscription costs are estimated for the traffic to/from all the vehicles (if covered by a single service provider) • Estimated subscription costs per vehicle per year (over ten years) are presented as alternative. • Refer to Section 0 and Annex C for model description • Results are presented in Section 5
Dedicated RSU-based V2I infrastructure	• RSU deployment costs are the responsibility of the service provider • Possible costs for road infrastructure upgrades are out of scope for the cost analyses (but alternatives are described in Annex A.3.3) • Accumulated cost over ten years are presented in Section 5 based on the considerations presented in Section 0	• RSUs O&M costs are assumed to be covered by the service provider • Possible costs for O&M of new road infrastructure components are out of scope for the cost analyses (but described in Annex A.3.3) • Accumulated cost over ten years are presented in Section 5 based on the considerations presented in Section 0	• No connectivity costs to communicate with vehicles associated with this technology (refer to Section 0) • Possible connectivity costs to connect RSUs with backend inf. are out of scope for the cost analyses (but described in Annex A.3.3)

NOTE: "costs" are seen from the service provider perspective, e.g., a Road Authority, an MNO or OEMs, as applicable.

4. Technical and deployment considerations for different solutions

In this section, the scope and considerations for the two alternative solutions are elaborated. This analysis includes the components required to relay information to or from vehicles, excluding any necessary infrastructure upgrades (as further elaborated in Annex A, Section A.3).

4.1 Existing cellular network infrastructure for delivering services via V2N2I communications

In order to deliver V2I services using cellular infrastructure, the system needs to:

- Enable the ITS backend to anonymously track the vehicle position in real-time, up to a predefined resolution (e.g., a "tile", or road segment, with an edge from hundreds of meters to a few kilometers). This functionality would normally reside with the OEM since the OEM would secure user consent and information about its vehicle's whereabouts for other reasons.
- Deliver unicast notifications of geographical relevance to the vehicles within certain "tiles", based on appropriate source of information. This functionality would normally reside with the OEM.
- Provide end-to-end security framework to obtain and maintain certificates.

- Depending on the business model, apply specific charging and contract policies to V2N2I traffic, which differ from other V2N or connected infotainment traffic exchanged with the vehicle.

This framework might be further optimized in several ways, for instance, by using cellular broadcast instead of unicast delivery. This is left for further investigation, so the approach here can be a conservative baseline case. The detailed analysis in Annex C provides an estimation of the cellular traffic demand per road type. Traffic separation and prioritization for V2N2I is implemented by the MNO depending on needs. This allows the MNO to track traffic and, if desired, to apply specific charging policies and Quality of Service (Priority) for V2I services.

It is worth noting that delivery of V2I services over cellular infrastructure (V2N2I) can be provided only where there is coverage and the appropriate SLA is in place. For example, in Europe, mobile networks are expected to achieve population coverage of 86% in rural areas and 97% in urban areas in 2019 [7]. By 2029 these values are expected to raise to approximately 95% in rural areas and 98% in urban areas. It is worth noting that, by 2029, 5G is expected to be widely deployed and to complement 4G in many areas. This study assumes 10 years for full V2N2I service deployment in the vehicles, an assumption that is conservative for cellular [7].

Even though LTE networks typically fulfil end-to-end (e2e) latency requirements well below 100ms [19][1], which is typically assumed for latency-critical ITS services, the performance may occasionally drop below expectations, which may determine service degradation because the network is best-effort unless prioritization is enabled. However, the services discussed in this paper are considered to be of informational and awareness nature according to C-ITS platform final report [1], and in future, prioritization can be enabled to meet latency targets if necessary.

No additional costs for security are considered, since certificate deployment in vehicles is required in either case. Moreover, communications over cellular networks is protected using non-compromised state of the art security specified by 3GPP, with continuous investment and improvements. 3GPP also governs security for cellular network nodes placed in accessible areas. The components to consider for this study are highlighted in red in Figure 3 and the assumptions and limitations are elaborated in Annex A. Additionally, network resilience, recovery and alternative back-up power modes including generators and batteries are typical for cellular networks to minimize network outages.

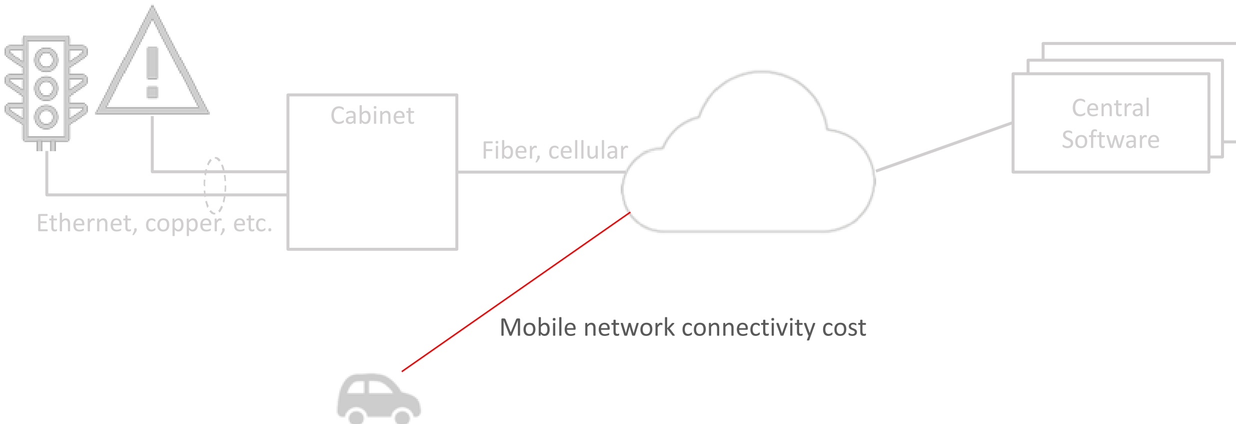


Figure 3: Cellular network key components for cost comparison.

4.2 Dedicated RSU-based V2I infrastructure

In order to deliver V2I services using RSUs, the system needs to:

- Deploy and connect RSUs to the appropriate source of information (e.g., a traffic controller, for security to a Public Key Infrastructure and related Certificate Authority.)

- Enroll RSUs and vehicles in the C-ITS security framework to obtain and maintain certificates. (Certificates are used to sign every message sent on short range communication to prove authenticity and validity of sender).
- Deliver the associated DENM messages periodically to nearby vehicles.

We note that the above framework is simplified, since it does not account for the case where RSU data needs to be exchanged with the backend system. In such cases, additional data (and costs) would need to be accounted for, particularly if the RSU is connected using a network that is not fully owned by the Road Authority, be it wired or wireless and further, this analysis does not account for the deployment of new backhaul infrastructure in cases where it is needed, which may be more than the cost of deploying the RSU itself. Furthermore, additional security measures are needed, both to secure backhaul connectivity and the equipment itself since it is placed in open areas. The technical analysis in Annex D provides an estimation of the RSU deployment volumes for different road types.

From a technical perspective, most short-range communication analysis work has focused on V2V rather than V2I. Nevertheless, the V2V performance expectations can be roughly applied also to V2I, due to the fact that the same radio technology and, likely, the same chipset will be used in On-Board Unit (OBU) and RSU. It is expected that the same radio spectrum with respective channel properties will be used for V2I and V2V for maximized inter-operability, resulting in increased channel load and consequently shorter range because only receivers close by will successfully decode a message in situations of high interference. RSUs may benefit from higher power, antenna position on high poles and slightly improved antenna directivity and reduced shadowing, compared to OBUs, which will correspondingly increase the link performance.

Similar to V2V, it is also expected for V2I that PC5-based V2I will deliver improved performance compared to 802.11p as used in both DSRC and ITS-G5, primarily due to the superior radio access technology. Based on the 5GAA performance test report on [8], field tests have shown that C-V2X has up to a 3.4x range advantage over DSRC. Early evaluations by 3GPP [9] indicated sufficient range for “event triggered” V2V traffic, such as DENM which is typically used for V2I.

Due to the above considerations, V2I coverage is expected to be better than V2V. The components to consider for this study are highlighted in red in Figure 4 and the assumptions and limitations are elaborated in Annex A.

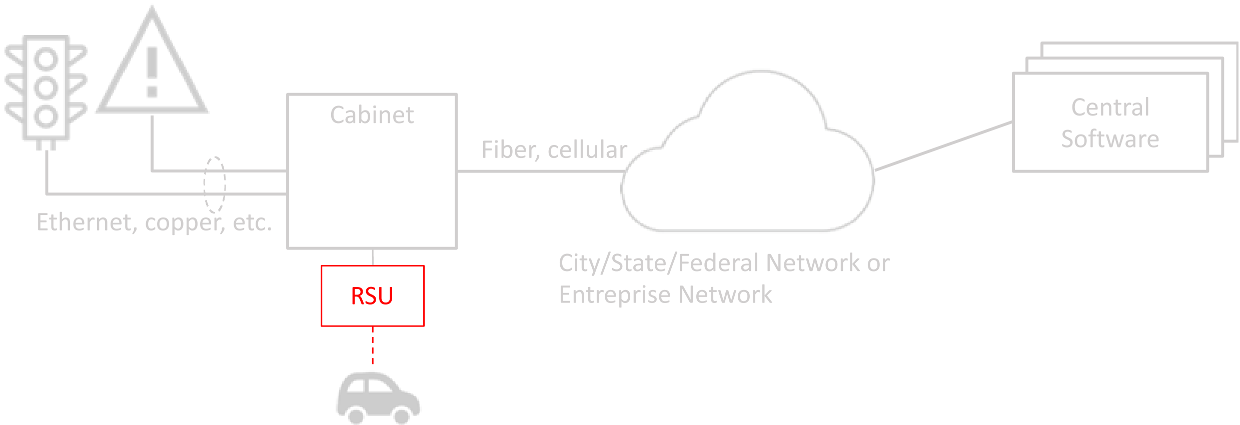


Figure 4: RSU key components for cost comparison.

4.3 Road infrastructure upgrades

Road infrastructure upgrades are required in order to deploy most V2I (or V2N2I), regardless if cellular networks or RSUs are ultimately used. In some cases, there is fibre and power available, but cabinets have to be installed. Moreover, road infrastructure and/or RSUs need to be connected to the backend system, and such backend system needs to be able to monitor events according to requirements—in some cases the service delivery might work with minimal integration with the infrastructure; however, some level of integration is always required with central systems for security certificate distribution. Some regions and cities already have upgraded infrastructure, which is commercially accessible over the Internet. While this can significantly reduce the costs for providing V2I (or V2N2I) services, is not a pre-existing condition in many cities where different (and sometimes multiple) traffic control systems coexist. For this reason, understanding the complete deployment costs for each region and cities correspond to a separate analysis that is not within the scope of this white paper. 5GAA has identified the need for such studies in the future and they will be based on the options elaborated in Annex A, Section A.3.

5. Deployment (CAPEX), Operation and maintenance (OPEX), and communication costs

The cost analysis is divided in three aspects to facilitate the comparison:

- Deployment cost (CAPEX).
- Operation and management costs (OPEX).
- Connectivity cost.

Each is presented in the following sections, for existing cellular networks and RSU solutions.

5.1 CAPEX: Infrastructure deployment costs

5.1.1 Existing cellular networks deployment cost

In this study we assume that the existing cellular networks are capable to satisfy the demand for the C-ITS V2I priority services considered. No additional infrastructure investment is needed on MNO side—of course, there is the possibility to include additional features in the networks (such as QoS support), but these will not be reflected in the cost calculations. Additionally, public-private-partnership (PPP) models to facilitate infrastructure expansion by MNOs to better support automotive requirements should also be considered and are currently being studied in 5GAA.

5.1.2 RSU deployment cost

For the inter-RSU distance, values between 300-1000m are used, following the model by the DG MOVE Study on the Deployment of C-ITS in Europe [4][15]. It is considered that motorways have a higher density of RSUs, while rural minor roads have the lowest density of RSUs [5]. For guidance purposes, the calculations in this study consider the estimated costs provided in the Analysis Mason report [10] for the practical purpose of the study, and additional costs elements elaborated in the ASSHTO 2014 report [5]; the details are further elaborated in Annex D. Such cost accounts for the RSU hardware as well as installation and planning costs. It is assumed that RSUs are deployed over a 10 year period with a 10% yearly deployment rate. We remark that such RSU deployment is chosen for the sake of fair comparison with cellular, assuming similar service penetration rate[16]. External studies assume a significantly lower RSU deployment pace, especially for rural areas [7], which would in practice result in reduced safety and efficiency benefits compared to the cellular solution.

5.2 OPEX: Operation and maintenance costs

5.2.1 Cellular networks operation and maintenance costs

Similar to the case of the cellular network deployment cost, we assume that the operation and maintenance costs are the responsibility of the MNOs. For this study we assume that these costs are reflected in the

[15] Based on the 300-500 range provided in Report for DG MOVE [4] on page 192 (refer to Annex D for additional clarification). https://ec.europa.eu/transport/sites/transport/files/2016-c-its-deployment-study-final-report.pdf

[16] Actually, the slower vehicle penetration of short-range compared to cellular connectivity would in any case determine additional safety benefits with cellular V2I.

subscription fees for connectivity. PPP models to facilitate infrastructure maintenance by MNOs to better support automotive requirements should also be considered in 5GAA.

5.2.2 RSU operation and maintenance costs

For the management and maintenance costs per RSU the calculations in this study consider the estimated costs provided in the Analysis Mason report [10], and additional costs elements elaborated in the ASSHTO 2014 report [5], such as an annualized replacement cost for RSU with the conservative assumption of having RSU replacement every ten years on average; the details are further elaborated in Annex D.

5.3 Connectivity cost

5.3.1 Cellular networks connectivity cost

Annex C provides an indication of the traffic delivered over cellular network to enable V2I. In order to quantify the associated connectivity cost, the reference cost per bit is needed. In Annex C it is shown that the V2N2I traffic per vehicle is quite limited. On the other hand, MNOs could enroll millions of new subscribers (as SIMs in vehicles), with the opportunity to also deliver additional V2N services such as telematics, software/maps transfers, connected Infotainment, etc., which may generate larger traffic demands and connectivity value. It is clear that MNOs may consider different strategic aspects when providing an offer for V2N2I traffic, but a cautious approach is adopted in this paper.

This study adopts a conservative approach based on commercially available offers for “on demand” data for private customers[17]. An average subscription cost estimation has been considered from the public report by the Swedish Post and Telecom Authority (PTS) [18]. These average subscriptions revenues per device are presented for services that could be global, which means that some subscriptions are used abroad, as elaborated in Annex C. In addition, it is assumed that the bit cost decreases 20% each year, following the historical trend that the price per bit over cellular network decreases 10 times over 10 years (i.e., per mobile “generation”). Even though such estimation is highly uncertain, different references assume a similar or more aggressive cost/bit trend with 5G [11][12].

In order to compare the technical solutions fairly, also for cellular-based V2I it is assumed that the service is deployed in vehicles at a 10% yearly penetration rate. However, we remark that in the cellular case a faster actual service penetration is expected [7], which would result in additional safety and efficiency benefits compared to the RSU solution.

5.3.2 RSU connectivity cost

There are no recurrent connectivity costs for this technical solution with regard to the direct communication with the vehicles. Nevertheless, in certain cases RSUs would use cellular or other leased communications for backhaul; this will require a subscription to a mobile operator or similar. In any case, this cost is considered part of the infrastructure upgrade cost and is excluded from the current analysis (as elaborated in Annex A, Section A.3).

5.4 Leveraging on existing cellular networks and complementary RSUs

Considering all the costs presented in the previous sections, it is possible to analyze a realistic deployment which considers a combination of existing cellular networks and complimentary RSU functionality. V2I delivery using RSUs may be considered as a solution for specific areas and services where the service provided by existing cellular networks is insufficient, such as poor coverage areas where no MNO has immediate deployment interest.

This option consists of a combination of the deployment considerations presented in Sections 4.1 and 4.2, which does not consider collocation or integration of small cells and RSUs. For analysis purposes, cellular networks are considered the baseline technology and adding RSU functionality depends on the service

[17] The conservative approach results in high costs sine it does not consider other services over the same link which might render cost of V2N2I element largely irrelevant, e.g. re-using an existing connection such as OEM telematics link.

requirements. A similar approach has been used in [5] to compare different fractions of RSU deployments in intersections; with 20% representing highest-volume intersections. The detailed scenario analysis is presented in Annex B.

6. Business comparison summary

Within the scope of the study, this section presents different analysis results to show the implications of having the possibility to use different technologies for the delivery of C-ITS services in scope.

6.1 Regional analysis

The region of Great Britain is used as an example, due to largely available detailed public data, with all the considerations detail in Annex B, Section B.1. Based on the description in previous sections, Figure 5 shows the average cost for a Service Provider (e.g., a Road Authority) covering all costs to relay information to/from vehicles (CAPEX, OPEX and connectivity).

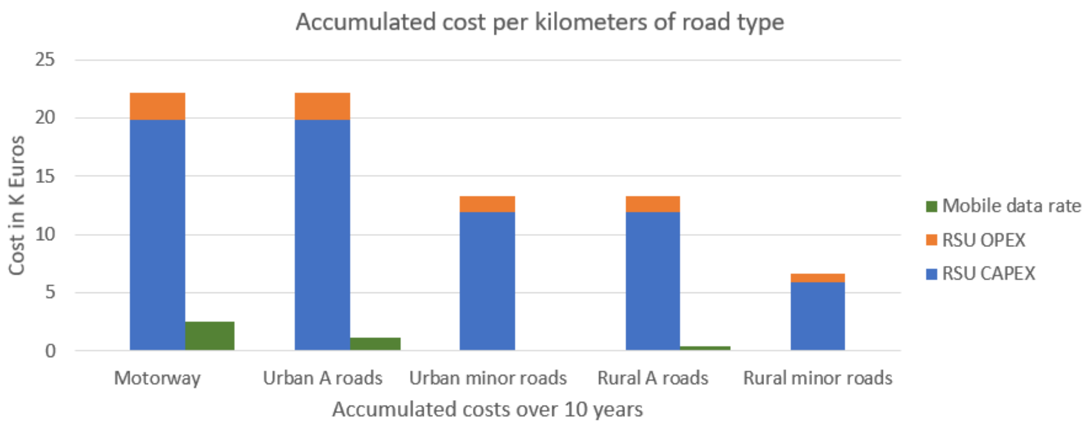


Figure 5: Cumulative cost comparison for different technical options, if the service provider (e.g., Road Authority) covers all costs.

The cumulative results in Figure 5 show that, from a cost perspective, relying only on RSUs would drive up the expenditure on infrastructure. We compare to the extreme case in which cellular communications (Uu) using existing cellular networks rather than deploying dedicated infrastructure with RSUs. It is quite impressive to see how the cost of the two technologies differs, for comparable service penetration in the market. One reason that explains the cost difference between motorways compared to rural roads is the required inter-RSU distance, which is assumed to be three times greater in rural minor roads compared to motorways and urban A roads (as elaborated in Annex D).

A linearly increasing full deployment on road connectivity infrastructure and vehicles is assumed over a 10 year period. In order to provide more granular results, three types of roads are considered: motorways, urban minor roads and rural minor roads.

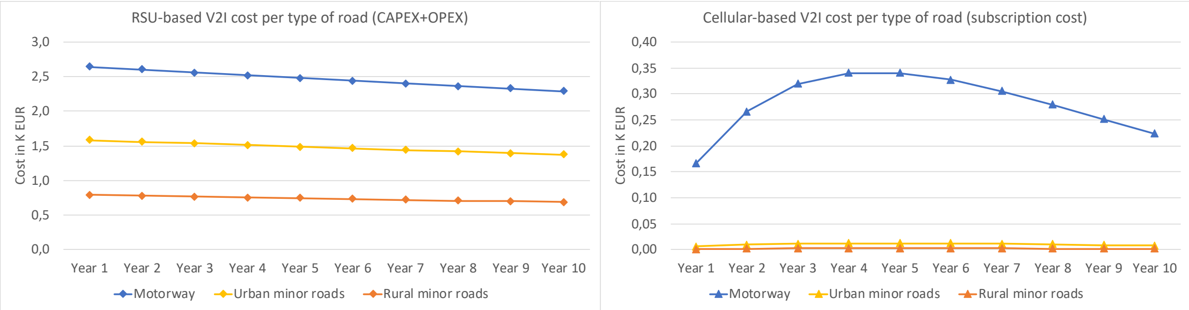


Figure 6: Yearly cost comparison for different technical options, if the service provider (e.g., Road Authority) covers all costs.

The results in Figure 6 highlight important aspects:

- If ITS services have to be delivered uniformly over all roads, the cost of delivering ITS services with existing cellular networks is significantly lower compared to widespread RSU rollout: in the best cases it could be even more than a hundred times lower than with only dedicated RSUs;
- The cost gap between RSU and cellular is larger for rural and minor urban areas and lower (but still very significant) for motorways and major urban roads.
- The cumulative connectivity cost is not offset even within 10 years, by which time 5G will be the common cellular standard and a new standard might already be in deployment phase.
- It is not a common business assumption to consider that road authorities should pay for cellular subscriptions in vehicles. In the case that the OEM or vehicle owner pays connectivity, and not the RO, it is feasible to assume that the portion of data transmitted in relation to the services considered for this study would represent a small fraction, compared to infotainment and other V2N services.

V2I delivery using RSUs may however be considered as a solution for specific areas and services where the service provided by existing cellular networks is insufficient, such as poor coverage areas where MNOs do not have deployment interests, or to facilitate some specific use-cases which are best served by RSUs. However, for such areas, and in general to improve the delivery of services over cellular networks, PPP between Road Authorities and MNOs may also be considered to facilitate MNO investments. Further PPP opportunities include infrastructure-sharing, where Road Authorities or dedicated 'Tower companies' provide infrastructure hosting and sharing opportunities towards MNOs in order to increase MNO incentives to expand network coverage to areas with low traffic demand. Such opportunities are not explored in detail in this whitepaper, but they will be addressed by future 5GAA work.

6.2 Intersection-based analysis in a city

Finally, a cost deployment analysis is presented in order to show different levels of complementarity between RSU-based and cellular-based alternatives to provide C-ITS services. These results are limited to intersection deployment, as detailed in Annex B, Section B.2. The costs related to road infrastructure upgrades are not part of the results, but it is assumed that such costs are similar regardless of the solution to use since they are more dependent on the pre-existing road infrastructure conditions; any upgrades would follow one of the alternatives exposed in Annex A, Section A.3.

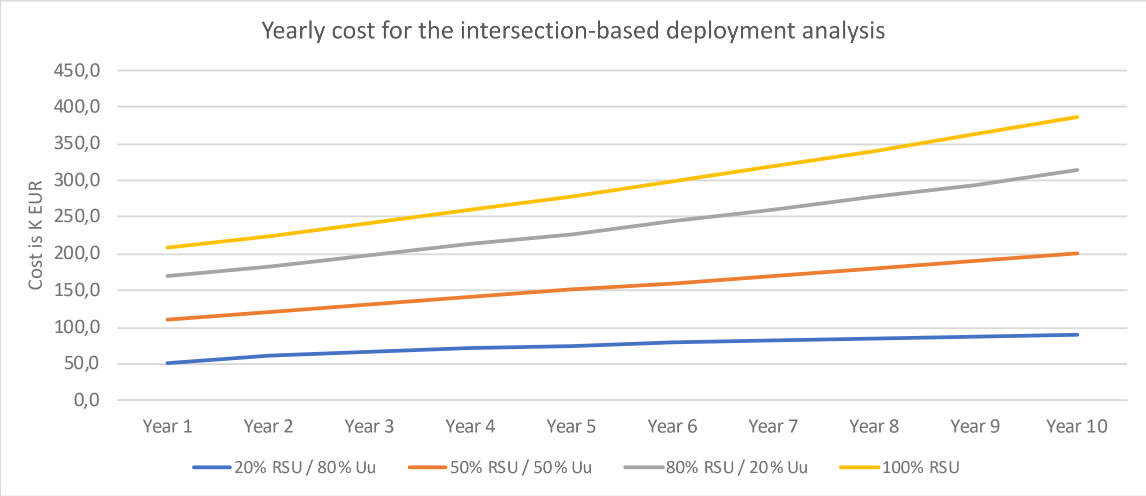


Figure 7: Cost evaluation for 262 targeted intersections in the city of Coventry.

These results showcase the benefits of having the possibility and flexibility to use a combination of RSU and Uu solutions in the same city. The definitive reason to select one solution or the other depends on several factors, such as cellular network coverage, degree of modernization of the road infrastructure and the desired direction to be taken by local road authorities depending on their specific context.

In some areas it might be difficult to rely on cellular communication for V2N2I, depending on available infrastructure or willingness of MNOs to be involved in such services. However, it is evident that using cellular communications in certain case (in this example, for services associated intersections such as GLOSA or priority request), result in significant costs reductions, comparing to relying solely on RSU deployments.

7. Conclusions

Taking into account the limitations highlighted in the study, it is evident that leveraging existing cellular networks for C-ITS V2N2I can reduce the implementation and delivery costs substantially: potentially by orders of magnitude. Based on the analysis in this whitepaper, Road Authorities should closely evaluate different ways to deliver C-ITS V2I priority services so they can deliver on the goal of accelerated and widespread uptake of C-ITS in vehicles and in road network ITS systems in order to prevent millions of road deaths and injuries each year; to enrich the economic fabric of countries by enabling better journeys; and to optimize the use of existing and future expensive road network infrastructure physical assets.

In addition to wide area cellular coverage, C-V2X offers support for services with stricter latency requirements over the short-range PC5 interface by deploying RSUs where they are needed. It is of utmost importance that Road Authorities are able to take advantage of the benefits of providing these services with a mix of technologies, including both short range and cellular wide area networks. Legislative barriers that prevent the use of cellular networks for service delivery in Road Authorities deployments may result in unnecessarily higher costs for V2I service delivery for governmental authorities and, unavoidably, taxpayers – and may become a fundamental barrier to providing services in some areas at all.

PPPs should also be considered to further expand MNOs capabilities to support ITS and automotive Services, however this topic is saved for a later contribution by 5GAA.

References

[1] C-ITS Platform “Final report” of January 2016. [Accessed on 05-07-2018] https://ec.europa.eu/transport/sites/transport/files/themes/its/doc/c-its-platform-final-report-january-2016.pdf

[2] Department of Transport Statistical Release “Road Traffic Estimates: Great Britain 2016” April 2017 [Accessed on 05-07-2018] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/611304/annual-road-traffic-estimates-2016.pdf

[3] Department of Transport Statistical Release “Road Lengths in Great Britain 2016” April 2017 [Accessed on 05-07-2018] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/611185/road-lengths-in-great-britain-2016.pdf

[4] DG MOVE “Study on the Deployment of C-ITS in Europe: Final Report Framework Contract on Impact Assessment and Evaluation Studies in the Field of Transport MOVE/A3/119-2013-Lot № 5 "Horizontal"” February 2016 [Accessed on 05-07-2018] https://ec.europa.eu/transport/sites/transport/files/2016-c-its-deployment-study-final-report.pdf

[5] American Association of State Highway and Transportation Officials (AASHTO) report “National Connected Vehicle Field Infrastructure Footprint Analysis” June 2014 [Accessed on 05-07-2018] https://rosap.ntl.bts.gov/view/dot/3440

[6] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/632857/nts0901.ods

[7] Ricardo Energy and Environment report “Safety of life study”, Report for 5GAA, 2018

[8] 5GAA, V2X Functional and Performance Test Report; Test Procedures and Results, November 2018

[9] TR 36.885, “Study on LTE-based V2X Services; (Release 14)”, 3GPP

[10] Analysis Mason “Socio-Economic benefits of Cellular V2X” report for 5GAA, 2017

[11] Ericsson, “The 5G Business Consumer Case”, 2018 [Accessed on 05-07-2018] https://www.ericsson.com/assets/local/narratives/networks/documents/report-eab-18000943-rev-a-uen.pdf

[12] K. Elleithy, W. M. Elmannai, “Cost Analysis of 5th Generation Technology”, CAINE-2014, 27th International Conference on Computer Applications in Industry and Engineering https://www.researchgate.net/publication/265168117_Cost_Analysis_of_5th_Generation_Technology

[13] http://converge-online.de/?id=000000&spid=en

[14] ARCEP Coverage and Quality of Mobile Services website: https://www.arcep.fr/index.php?id=13711&L=1

[15] ARCEP document: “Results of the work done on achieving ubiquitous, high standard mobile coverage for every person in France ". 22 January 2018. https://www.arcep.fr/uploads/tx_gspublication/description-dispositif-couverture-mobile-ENG-220118.pdf

[16] Catherine Stupp (EURACTIV.com), “Big telcos take the stage in Germany’s new spectrum auction”. May 27, 2015. Available online: https://www.euractiv.com/section/digital/news/big-telcos-take-the-stage-in-germany-s-new-spectrum-auction/

[17] European Parliament, “Transport MEPs welcome Commission strategy to boost connected and automated mobility”. February 20, 2018 [Accessed on 05-07-2018] http://www.europarl.europa.eu/news/en/press-room/20180219IPR98108/transport-meps-welcome-strategy-to-boost-connected-and-automated-mobility

[18] Swedish Post and Telecom Authority (PTS), “The Swedish Telecommunications Market 2017” Report number: PTS-ER-2018:16. May 2018 [Accessed on 27-09-2018] http://www.statistik.pts.se/media/1373/swedish-telecommunications-market-2017.pdf

[19] ETSI TR 102 962, Intelligent Transport Systems (ITS); Framework for Public Mobile Networks in Cooperative ITS (C-ITS), 2012.

[20] OpenSignal, State of Mobile Networks: USA (July 2018). https://opensignal.com/reports/2018/07/usa/state-of-the-mobile-network

Annex A: Scope and Limitations

A.1 Application requirements for transmissions

In the ETSI TS 101 539-1[18], dealing with Road Hazard Signaling application requirements, C-ITS services are grouped on a time frame based on the Time-To-Collision. The groups and possible message types usages are:

- The "driver information" may be achieved by digital radio broadcast channels or cellular network using TPEG or "In-Vehicle signage" (IVS) covering fixed or variable message sign information such as currently under specification by road operators.
- The "driver awareness" may be achieved with the RHS application upon reception of CAMs and DENMs.
- The "driver warning" may be achieved with the ICRW and the LCRW applications upon reception of CAMs and DENMs from neighboring ITS-Ss.

It is also worth mentioning that there is priority level included in the field of a DENM message. This priority level is linked to the traffic safety situation based on the Time-To-Collision, providing three levels of priority: driver awareness situation (level 2), warning situation (level 1), pre-crash situation (level 0).

DENM messages with priority level 2 could transmitted over current cellular networks without specific optimization features. In case of a higher priority level, latency and reliability optimizations should be planned such as improved QoS support and local breakout solutions within mobile networks. For the C-ITS platform V2I services described as Day 1/1.5 applications, we limit the scope of the study at driver information and awareness time frame since these Day 1/1.5 applications are considered to be of informational nature according to the C-ITS platform final report in its Chapter 5.3.1 (which discusses liability) [1].

A.2 Combined cellular networks and RSU

Whereas there are activities to deploy RSUs by road authorities and there are also unrelated efforts underway to further build out and/or upgrade the cellular network with additional base-stations (eNB/Small Cells) to support 4G and 5G network coverage and densification, there is also the possibility to deploy infrastructure that combines the functionality of both types of aforementioned equipment into a single device that we can refer to as a Combined Small Cell + RSU, leveraging wired/wireless backhaul. In fact, members of 5GAA are exploring the possibility of combined infrastructure in what could be a public-private partnership, and there is significant interest in exploring this given that Mobile Network Operators (MNOs) have substantial experience deploying, managing and maintaining wireless infrastructure. Further, in many scenarios, there might be a possibility that an RSU and a Base-Station/Small Cell may be located in proximity anyway. Although this deployment configuration is not studied in this whitepaper. This infrastructure concept shouldn't be confused with the notion of a Connected RSU, as they are entirely different. A Connected RSU is wireless infrastructure enabled with short-range communications (PC5) and has either wired/fiber backhaul or uses the cellular network (Uu) as a wireless backhaul.

A.3 Road infrastructure upgrades for existing cellular networks and RSUs

In some parts of the world traffic light status, variable road signs etc. are already available on Internet on commercial terms, as presented in Section 0. However, if connected infrastructure is not in place, additional infrastructure upgrades are required in order to deploy V2I (or V2N2I), regardless of the technical solution to implement; for example, road infrastructure and/or RSUs need to be connected to the backend system, and such backend system needs to be able to monitor events according to requirements. Using RSUs or

[18] ETSI TS 101 539-1; Intelligent Transport Systems (ITS); V2X Applications; Part 1: Road Hazard Signalling (RHS) application requirements.

cellular connectivity (Uu) does not dictate what happens between local cabinets and central software. Cellular or fiber could be used in both cases, so it is a common cost.

Figure 8 presents a high-level representation of the road infrastructure connectivity, where traffic lights and signs are connected to cabinets which host the related controllers. These cabinets are then connected to remote servers.

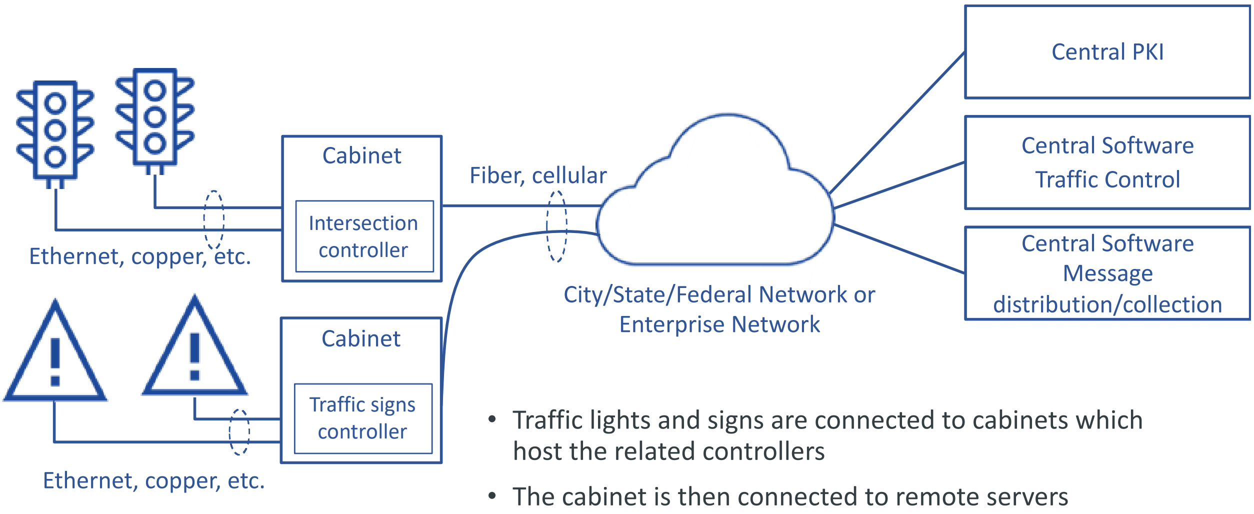


Figure 8: Road infrastructure connectivity.

Traffic controllers at intersections have largely been unconnected, with small instances of copper wire twisted pair, fiber optics, and/or some aftermarket cellular-enabled wireless routers. With the accelerated interest in smart cities, connected mobility, and the internet of things, traffic controller vendors are looking to not only advance the state of electronics in the controller itself, but also connect it. The connections they are looking to add natively in their controller offerings include backhaul connectivity – allowing for central traffic management, firmware updates, reprogramming, traffic analysis, support sensor collection including live video streaming, and to share Signal Phase and Timing (SPaT) data through the cloud. At the same time, the growing interest in connecting vehicles directly to traffic intersections also means interest in enabling communications to vehicles to support a variety of intersection safety services. As a result, traffic controller upgrades will see the addition of embedded network-based (Uu) and direct communications (PC5), so this presents yet another deployment option – though we do not study that in this whitepaper.

For countries or regions where traffic controllers are not yet connected (as discussed earlier in this chapter), investments for such infrastructure upgrade are highly dependent on the pre-existing conditions and decisions from ROs. The required components, depending on the solution to implement, are presented next. It is worth noting that different options should be able to coexist within the same region or city, since the same level of service could be accomplished. Three architectural approaches are explained:

- Cellular based, considering local processor units.
- Cellular based, considering traffic/signal controllers upgrade.
- RSU based, considering optional cellular backhaul link.

Some components described below may result in additional costs, this entirely depends on the existing status on the infrastructure, which varies in every city and region and should be subject of further (dedicated) analysis.

A.3.1 Cellular based architectural approach with local processor units

This approach is relevant when a RO or metropolitan traffic authority opts to relay information to vehicles over V2N2I without updating existing traffic or signal controllers inside road cabinets. In order to generate and report certain local messages, it is necessary to deploy additional processing modules, which can be installed in existing roadside cabinets.

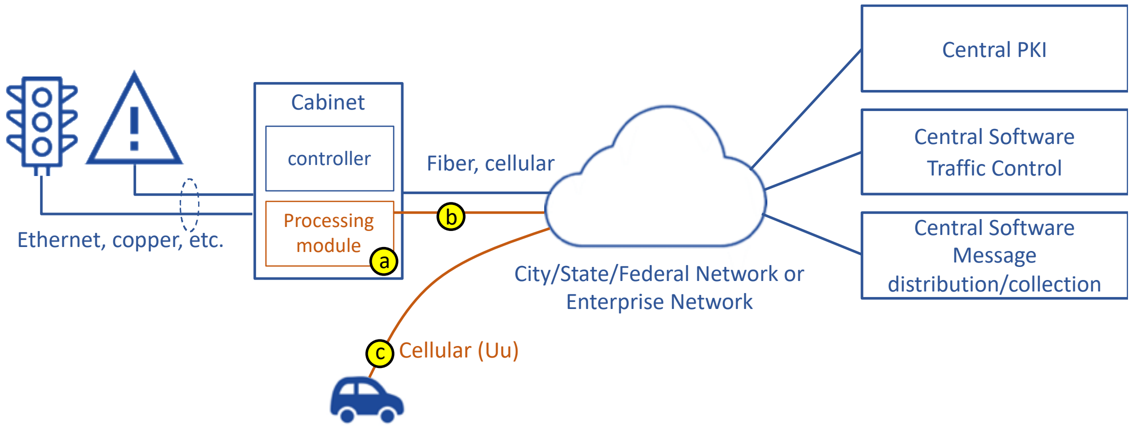


Figure 9: cellular-based approach with local processing unit and infrastructure implications.

Figure 9 depicts the cellular-based architecture approach with local processing unit. The three architectural components are denoted with letters a, b, and c, and are summarized as follows:

a) *Processing module*: for generating and reporting (for instance, SPAT/MAP or other local messages) to backend systems. This type of processing unit is required if the available traffic controllers do not report this information already (hence, it could result in additional costs, depending on pre-existing infrastructure in cabinet). One observation is that such processing module will only cost a fraction of a full-fledged RSU, since it does not require radio planning or ruggedized hardware.
b) *Connectivity for processing unit*: required if pre-existing cabinet connectivity is limited is capacity. This connectivity can be provided via e.g. city/state/federal or enterprise networks as well as via cellular links (e.g., Uu interface such as LTE) or by wire connections (e.g., fiber).
c) *Cellular subscription fee for the vehicle*: required to relay information to the vehicle over the Uu interface.

A.3.2 Cellular based architectural approach with controllers' upgrade

This approach is relevant when there is an ongoing upgrade of the existing traffic or signal controllers (as presented in the introduction of Section A.3). In this case, certain messages would be generated by central software and some upgrades in central systems are envisioned.

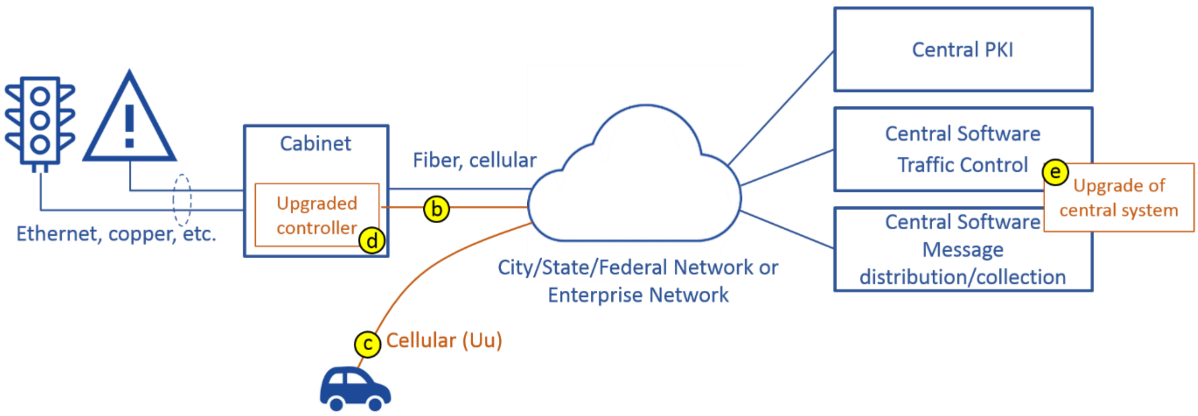


Figure 10: cellular-based approach with controllers' upgrade and infrastructure implications.

Figure 10 depicts the cellular-based architecture approach with controllers' upgrade and infrastructure implications. The four architectural components depicted are denoted with letters b, c, d, and e and are summarized as follows:

b) *Connectivity for processing unit*: the same as the architectural component *b)* in Figure 9.

c) *Cellular subscription fee for the vehicle*: the same as the architectural component *c)* in Figure 9.
d) *Upgraded controller in the cabinet*: necessary if pre-existing interaction between controller and backhaul requires improved backhaul connectivity to rely on an improved central system for generation of messages and application processing.
Note: Traffic Technology Services[19] in the US is already implementing the solution depicted in Figure 3-2 regarding the road infrastructure connectivity without requiring any updates of the controller. The Sydney Coordinated Adaptive Traffic System (SCATS)[20] system is also following the same approach without any upgraded controller in the cabinet. In Australia, where the system was first developed, the majority of signalized intersections are SCATS operated (around 11.000).
e) *Upgrade of the central system*: to process information coming from cabinet (this refers to specific software updates for specific services such as SPAT/MAP generation).

A.3.3 RSU based architectural approach with optional cellular backhaul link

Approaches based on RSUs must include a degree of integration with road infrastructure, at a minimum, they need to be connected to the backend system for certificate handling. In some cases, it is beneficial to use a dedicated cellular link from the RSU for these purposes. In this manner is possible to avoid expensive integration works with dated road infrastructure.

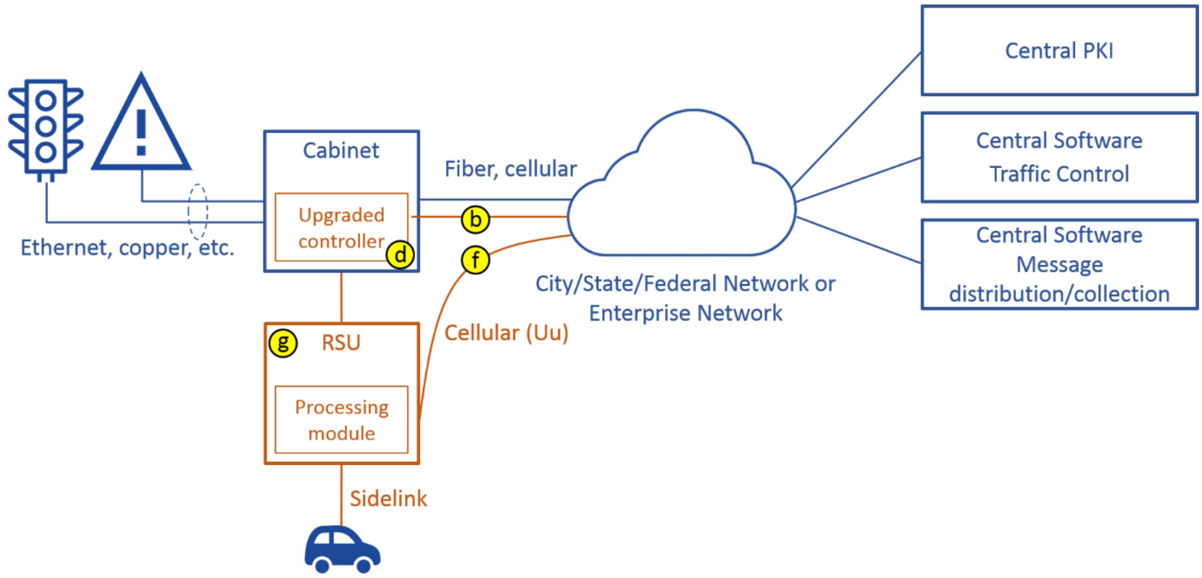


Figure 11: RSU-based architectural approach and infrastructure implications.

Figure 11 depicts the RSU based solution with optional cellular backhaul link and infrastructure implications. The four architectural components depicted are denoted with letters b, d, f, and g and are summarized as follows:

b) *Connectivity for processing unit*: the same as the architectural component *b)* in Figure 9.
d) *Upgraded controller in the cabinet*: the same as the architectural component *d)* in Figure 10.
f) *Cellular subscription*: used for backhaul connectivity (for instance, for certificate handling at central PKI), avoiding integration with pre-existing infrastructure in cities. It depends on pre-existing infrastructure whether the already existing connectivity at the cabinet can be re-used, similarly to infrastructure component *b)* of the cellular-based solution with local processing unit in Section A.3.?.
g) *RSU*: required to generate, send and receive local messages. It has associated costs related to planning, deployment and maintenance.

[19] https://www.traffictechservices.com/how-it-works.html
[20] https://www.mainroads.wa.gov.au/OurRoads/Facts/ITS/Pages/SCATS.aspx

A.4 Further considerations

As already mentioned, the architectural approaches and associated architectural components for inter-connection of road traffic infrastructure are highly dependent on pre-existing infrastructure. The study from a business perspective is highly dependent on pre-existing infrastructure and, therefore, separate studies should be considered for different implementation under study. Understanding such available infrastructure to perform a complete cost analysis is desirable and already discussed as a future 5GAA activity.

The following architectural components have been discussed:

a) *Processing module*: at the cabinet side, for generating and reporting (for instance, SPAT/MAP or other local messages) to backend systems. This type of processing unit is required if the available traffic controller do not report this information already. One observation is that such processing module does not require radio planning or additional ruggedized cabinets.

b) *Connectivity for processing unit*: required if pre-existing cabinet connectivity is limited in capacity. This connectivity can be provided via e.g. city/state/federal or enterprise networks as well as via cellular links (e.g., Uu interface such as LTE) or by wire connections (e.g., fiber).

c) *Cellular connectivity for the vehicle*: required to relay information to the vehicle over the Uu interface (to be considered in case of cellular-based connectivity for vehicles).

d) *Upgraded controller in the cabinet*: necessary if pre-existing interaction between controller and backhaul requires improved backhaul connectivity to rely on an improved central system for generation of messages and application processing.

e) *Upgrade of the central system*: to process information coming from cabinet at the central system (this refers to specific software updates for specific services such as SPAT/MAP generation).

f) *Cellular link for RSU backhaul connectivity*: used for backhaul connectivity (for instance, for certificate handling at central PKI), avoiding integration with pre-existing infrastructure in cities. It depends on pre-existing infrastructure whether the already existing connectivity at the cabinet can be re-used, similarly to infrastructure component b of cellular-based solution with local processing unit in Sec. 3.1.

g) *RSU:* required to generate, send and receive local messages (to be considered in case of RSU-based connectivity for vehicles).

The architectural approached presented in this annex represent some possible solutions considering cellular-based and RSU options. Nevertheless, the focus of this contribution is to highlight the potential architectural components required to upgrade existing road infrastructure connectivity and their relationship with the capabilities of existing infrastructures. The figures represent a guiding example depending on some implementation options and possible upgrade approaches.

Annex B: Study cases

B.1 Region wide analysis in Great Britain

In order to make a comparative study, a representative region has been selected, corresponding to Great Britain, due to largely available detailed public data [2][3]. Nevertheless, the outcome applies to most European states, if not globally. For this region, the areas to study for the cost calculations are [3]:

- Motorways: considering a total length of 3 701 km (0,9%)
- Urban A roads: considering a total length of 11 191 km (3%)
- Urban minor roads: considering a total length of 130 911 km (33%)
- Rural A roads: considering a total length of 35 703 km (9%)
- Rural minor roads: considering a total length of 21 421 km (54%)

Regarding the traffic, vehicle kilometers is used to represent the total distance travelled by all vehicles over one year. The following is considered [2]:

- 109 billion kilometers per year travelled on motorways
- 80 billion kilometers per year travelled on urban A roads
- 106 billion kilometers per year travelled on urban minor roads
- 151 billion kilometers per year travelled on rural A roads
- 73 billion kilometers per year travelled on rural minor roads

Table 2: Length and usage of various road types in Great Britain

Area	Length of roads (km)	Fraction of road length per road type	Fraction of total vehicle km per road type	Average traffic flow (vehicles/year)*
Motorway	3 701	0,9%	21,0%	29 478 261
Urban A roads	11 901	3,0%	15,5%	6 761 325
Urban minor roads	130 912	33,0%	20,5%	816 276
Rural A roads	35 703	9,0%	29,0%	4 228 082
Rural minor roads	214 219	54,0%	14,0%	341 823
Total	396 437	100,0%	100,0%	41 625 767

*Average use of each km in a year

B.2 Intersection-based analysis in the city of Coventry

In order to make a comparative study of the deployment cost on intersections, a representative city has been selected, corresponding to the city of Coventry, due to available detailed public data. Nevertheless, the outcome applies to most European cities with similar characteristics:

- The area for City and Metropolitan borough is 98.64 km^2.
- Road network length[21] has 2 312 km in total, consisting of 97 km of highway and 2 215 km non-highway.
- Total traffic on major roads by cars in 2 017 was 702 637 thousand vehicle kilometers[22].
- There is a total of 235 traffic controller sites (signalized locations).

Following the considerations given in [5], signalized and unsignalized locations are considered:

- Signalized locations: junction/crossing site with traffic lights.

[21] https://www.tomtom.com/en_gb/trafficindex/city/coventry
[22] https://www.dft.gov.uk/traffic-counts/area.php?region=West+Midlands&la=Coventry

- Unsignalized locations: junction/crossing site with no traffic lights that might be equipped with RSUs. In 2 015 there were 264 signalized locations and in 2 018 there are 235 (there is a trend to remove certain traffic lights in the city) [23].

Different deployment objectives are evaluated, with cellular networks are considered the baseline technology and adding RSUs depending on the needs.

Table 3: Different levels of RSU site deployment targets

Level of Deployment (RSU sites)	20% signalized + Unsignalized	50% signalized + Unsignalized	80% signalized + Unsignalized	100% signalized + Unsignalized
Signalized locations	47	118	188	235
Unsignalized locations	6	14	22	27
Total	53	131	210	262

According to the AASHTO report [5], 20% of intersections correspond to the highest-volume intersections, where half of the intersection crashes may occur. 50% would account for intersections where 80% of intersection crashes occur. 80% would account for relevant intersections.

For the cellular subscription costs, the model is based on the assumptions in Annex C. 9 events are considered per kilometer (roughly derived by considering the total length of road divided by the number of targeted intersections). For RSU calculations, the costs follow the model presented in Annex D. Note that cost adjustments should are made for the Uu subscription.

Table 4: Costs to cover 262 intersections in the city of Coventry

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
RSU CAPEX and OPEX (K EUR) considering 100% of the intersections	207,9	224,2	241,3	259,3	278,2	298,1	318,9	340,7	363,6	387,4
Cellular subscription (K EUR) considering data volumes for all intersections	11,7	18,7	22,4	23,9	23,9	22,9	21,4	19,6	17,6	15,6
Combined deployment options:										
20% RSU / 80% Uu (K EUR)	50,9	59,8	66,2	71,0	74,7	78,0	80,9	83,8	86,8	90,0
50% RSU / 50% Uu (K EUR)	109,8	121,4	131,8	141,6	151,0	160,5	170,2	180,1	190,6	201,5
80% RSU / 20% Uu (K EUR)	168,6	183,1	197,5	212,2	227,3	243,1	259,4	276,5	294,4	313,1

[23] http://www.coventry.gov.uk/download/downloads/id/20296/req00941.pdf

Annex C: Modeling of cellular-based V2N2I

The modeling procedure for cellular-based V2N2I is based on the following steps:

1. Assess the average amount of data exchanged to deliver V2N2I to a vehicle over a specific road section;
2. Assess the yearly vehicle km per type of road (in other words, how many times a single km of road is used by all vehicles during a year);
3. Combine 1) and 2) to obtain the average data exchange required to connect all vehicles on a certain type of road.

The first point depends on the technical details of the deployed V2I solution. In this study we consider the "geolocation" solution derived in the German public project CONVERGE [13], where the geographical areas are logically split in (semi)static tiles, e.g., 1 km x 1 km. Such tiles are known to both the backend and the application in the vehicle. Whenever the vehicle enters a new tile it informs the backend using a "tile update" UL message that we conservatively dimension as 2 kB each, including protocol overhead. The backend anonymously tracks vehicles belonging to each tile and, for each "V2I event", it delivers a V2(N2)I message (e.g., traffic signs) using DENM-like messages, which we conservatively dimension as 2 kB each [9], including protocol overhead. A "V2I event" can be a traffic sign, a traffic light phase, or a traffic-related notification.

Table 5: Data requirements (at 100% service penetration) for various road types

	Total vehicle km per year (km/year)	Average number of V2I events per km[24]	Total data transfer per year (bits)[25]
Motorway	109 113 252 000	[2+1]	5,23744E+15
Urban A roads	80 467 000 000	[5+1]	7,72483E+15
Urban minor roads	106 860 176 000	[3+1]	6,83905E+15
Rural A roads	150 956 092 000	[2+1]	7,24589E+15
Rural minor roads	73 224 970 000	[1+1]	2,34320E+15

The geographical density of events is hard to assess, but it is related to the expected inter-RSU deployment distance for a certain road type (see Annex D).

Table 5 provides the detailed assumptions. Vehicle km per road type are obtained from public statistics in the UK, and from them the data transfer requirements per road type, over a year. For the average number of events, it is assumed that the system is location aware. Otherwise, if the precise location of the vehicle is unknown, the data consumption will be higher (because the central server will send additional data points to make sure it covers the area where the vehicle is located).

The actual yearly connectivity cost depends on the cost/bit, which is expected to decrease by 20% per year based on historic trends and technological considerations [11][12]. This analysis is based on a commercial offer for "on demand" traffic, which carries over to 1,175E-09 Eur/bit in 2018. To reach this value for the cellular subscription, an average subscription cost per month is considered based on the values provided by the Swedish Post and Telecom Authority (PTS) for M2M subscriptions [18][26]. These subscriptions are for services that could be global, which means that some subscriptions are used abroad [18]. Since this value covers all M2M subscriptions, we assume additional service level agreements in the automotive case and therefore use three time the average subscription cost for the calculations, resulting in 2,4 EUR per month per vehicle for 255 MB of data.

[24] the "+1" indicates "tile update" to the backend system, with average 1km tile edge.

[25] With 100% service penetration in vehicles.

[26] Average income per subscription per month was 8 SEK (Swedish Kronor; equivalent to 0,8 EUR) in 2017.

Table 6: Estimated cost per bit

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
10^{-10} EUR/bit	0,12	9,4	7,52	6,016	4,81	3,85	3,08	2,46	1,97	1,58

The cost for a service provider delivering the V2I service is finally assessed by assuming linearly increasing (according to increasing penetration) yearly traffic to the level of Table 5, over a 10 years period. Such traffic is multiplied with the bit cost in Table 6, to provide the cellular results in Figure 6.

Annex D: Modeling of RSU-based V2I

In this section, the cost for RSU deployment is evaluated based on the following steps:

1. Assess the average amount of RSUs required to cover each road type;
2. Estimate the deployment CAPEX and OPEX costs per year, together with the deployment rate.

The first point depends on the inter-RSU distance. In this study we consider the range for RSUs to be in the range of 300-500m, based on the values provided in Report for DG MOVE [4] and the calculations are presented in Table 7. Noting that external studies assume a significantly lower RSU deployment pace for rural areas [7], for this reason, we assume an inter-cell distance of 1km for rural minor roads.

Table 7: Dimensioning of RSU deployment (Great Britain)

Area	Inter-RSU distance (m)	Length of roads (km)	Number of RSUs required
Motorway	300	3 701	12 338
Urban A roads	300	11 901	39 670
Urban minor roads	500	130 912	261 824
Rural A roads	500	35 703	71 406
Rural minor roads	1 000*	214 219	214 219
Total			583 590

*a sparser deployment is assumed for rural minor roads.

The cost for the network delivering the V2I service is assessed by assuming deployment rate of 10% per year, over a 10 years period. Regarding CAPEX, RSU hardware and installation costs are taken from the Analysys Mason report assuming to be in the order of 4 500 EUR/RSU [10]. An additional cost for radio design and planning is included, as suggested in the AASHTO report [5]. The CAPEX has a yearly price evolution of -2% [10]. Regarding OPEX, the RSU management and maintenance costs are directly taken from the Analysys Mason report, which assumes an estimated cost of 285 EUR/year/RSU [10], and an additional cost for RSU replacement [5], with the assumptions that RSU are replaced at a cycle of ten years base. OPEX is considered to have a yearly price evolution of 2% [10]. These costs are presented in Table 8.

Table 8: RSU costs references for CAPEX and OPEX

CAPEX Cost element	Cost per device (EUR)	Source
Hardware	3500	[10]
Installation	1000	[10]
Design & planning	2700	60% of hardware and installation costs, as in [5]
Total CAPEX	**7200**	
OPEX Cost element	Yearly cost per device (EUR)	Source
Power	20	[10]
Maintenance	225	[10]
Security	40	[10]
Annualized replacement cost (over ten years)	450	Base cost equivalent to hardware and installation, as in [5]
Total OPEX	**735**	

The cost for the network deployment and maintenance is assessed based on all the previous assumptions over a 10 years period as shown in Table 9. These costs are multiplied by the number of required RSUs, to provide the results in Figure 6.

Table 9: Estimated cost evolution for RSUs

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Deployment cost per RSU (adjusted) (EUR)	7 200	7 056	6 915	6 777	6 641	6 508	6 378	6 251	6 125	6 003
Maintenance cost per RSU (adjusted) (EUR)	735	750	765	780	796	811	828	844	861	878

5GAA is a multi-industry association to develop, test and promote communications solutions, initiate their standardization and accelerate their commercial availability and global market penetration to address societal need. For more information such as a complete mission statement and a list of members please see http://5gaa.org/