Safety of life study

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Report for 5GAA

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Executive summary

The aim of this study is to explore the impact of different technical solutions for Cooperative Intelligent Transport Systems (C-ITS) communication solutions on EU road safety over time. Three different communication solutions are assessed independently and consist of:

- Cellular vehicle-to-everything (C-V2X) communication based on the evolved LTE technology as defined by 3GPP (a global cellular specifications body), divided into two solutions:
    - LTE-PC5: Communication solution that uses direct-mode communication between vehicles, road users and infrastructure operating in ITS bands (e.g. ITS 5.9 GHz) independent of cellular network;
    - LTE-Uu (cellular): Network-based communications interface (Uu) operating in the traditional mobile broadband licensed spectrum;
- 802.11p[1] a Wi-Fi technology that supports Vehicle-to-vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications based on IEEE 802.11p and uses direct-mode communication operating in the ITS band of 5.9 GHz.

For the purpose of this study LTE-PC5 and LTE-Uu will be modelled separately. However, it should be noted that these would likely co-exist. When assessing the results presented in this study, it should be considered that in reality, these two technical solutions could complement each other.

A key motivation for introducing C-ITS is the major potential to help improve road safety and decrease the number, as well as the severity, of accidents. For this study we have focused on two specific C-ITS use cases with high accident reduction potential that are on the European Commission's list of priority C-ITS services [1]. The selected services address vehicle-to-infrastructure (V2I) and pedestrian/cyclist to vehicle (V2P) communications:

- Red signal violation/intersection safety;
- Vulnerable Road User (VRU) protection.

The approach taken in this study separately models the penetration of new vehicles with C-ITS through built-in systems and that of additional equipment in existing vehicles through the driver's smartphone (referred to as retrofitting).

We consider, as a baseline, the existing statistics of road traffic fatalities in the EU and then evaluate the potential reduction in the number of fatalities resulting from the deployment of each technical solution.

The modelling framework is kept in line with a previous 5GAA study [2] and considers:

- The likelihood that any two ITS stations (vehicles, VRUs, roadside units (RSUs)) involved in a potential accident will be equipped with the same C-ITS communication solution.
- The fraction of fatalities which could be addressed and mitigated by the considered C-ITS communication solution.
- The likelihood that data transmitted from an ITS station via a given C-ITS communication solution is successfully communicated to its intended recipient.
- The effectiveness of a received alert/warning message in appropriately affecting the behaviour of the driver of a vehicle travelling towards a potential accident.

To account for the uncertainty in predicting the extent of future deployment and reliability of C-ITS technologies, we have developed "high" and "low" scenarios showing the sensitivity to key input parameters.

[1] the terminology has been kept in line with the previous Ricardo study

Main results

Results are presented in terms of fatalities and serious injuries. Statistics on serious injuries from road traffic accidents at the EU level are not publicly available but it is estimated that for every death on Europe's roads there are 12 serious injuries[2] [3]. This assumption is used to estimate the total number of serious injuries which could be prevented.

The benefits of C-ITS (under all three communication solutions) for the red signal violation case are limited in the early years of deployment due to the need to roll-out C-ITS infrastructure and the associated management systems (whether through roadside units for 802.11p or LTE-PC5, or connection to the cellular network for LTE-Uu). The benefits from 802.11p are also reduced because of the lower alert delivery rates due to poorer technology performance for this technical solution, as well as the slower roll-out, as identified in previous 5GAA work [2].

The VRU protection use case shows greater benefits in early years as the take-up of the service is not dependent on the roll-out of roadside units and is largely available through the use of smartphone applications. Due to technical barriers for 802.11p roll-out in smartphones, this analysis found that corresponding solutions were infeasible and consequently only considered LTE-PC5 and LTE-Uu solutions for this case.

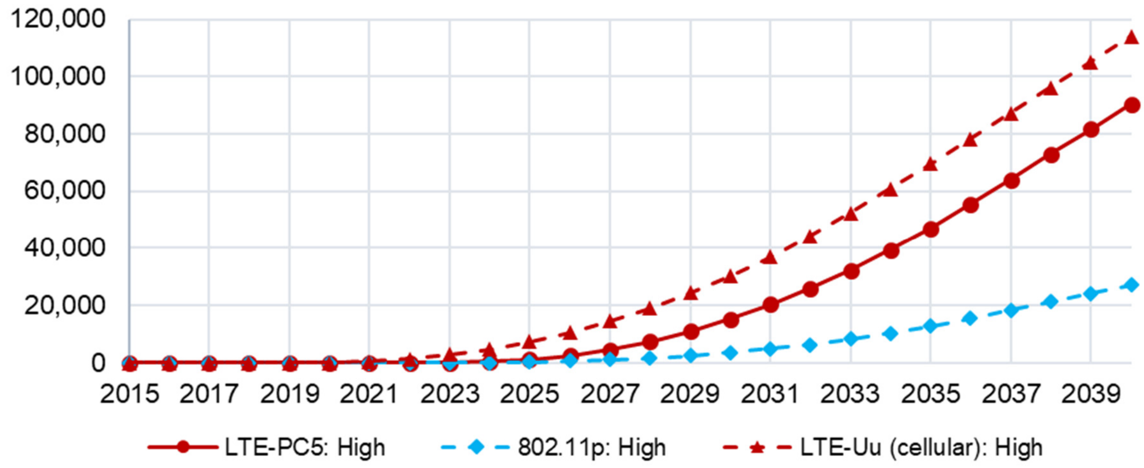
The analysis shows potential benefits exist from the application of C-ITS services to the red signal violation and VRU protection use cases. The overall number of fatalities and serious injuries saved is significantly greater in the VRU protection case, primarily because the VRU baseline has a higher number of fatalities than the red signal violation case.

In both use cases LTE-Uu (cellular) and LTE-PC5 C-ITS communication solutions deliver greater benefits than 802.11p. Due to insufficient data being available the analysis presented in this report is based on 4G-LTE cellular communications only. This may be under-estimating the benefits of the roll-out of LTE-Uu (cellular) communication solution because the potential benefits of 3G and 5G, to supplement 4G, are not considered. While we have modelled LTE-PC5 and LTE-Uu separately, in practice the two technical solutions will complement each other because both utilise very similar chip technology. It is likely that LTE-PC5 could be introduced in addition to LTE-Uu, potentially providing C-ITS capability in areas with poor network coverage or for applications that would benefit from direct communications.

The aggregated results for both use cases (without the additional benefit arising from retrofitting of C-ITS services through apps on smartphones used in vehicles), as shown in Figure 1, illustrate that in the high scenario LTE-Uu shows the highest benefits in terms of the number of avoided fatalities and serious injuries. By 2040 the number of fatalities and serious injuries avoided through the use of the LTE-Uu solution reaches 114,066, compared to 90,380 for LTE-PC5. For the 802.11p solution the values are significantly lower at 27,144 as VRU protection is not supported through smartphones, leading to a low level of VRU protection (where VRUs are expected be equipped with C-ITS technology through their smartphones). Research carried out for this study showed that integration of 802.11p into smartphones is highly unlikely; thus, the penetration in smartphones for this technical solution was set to zero.

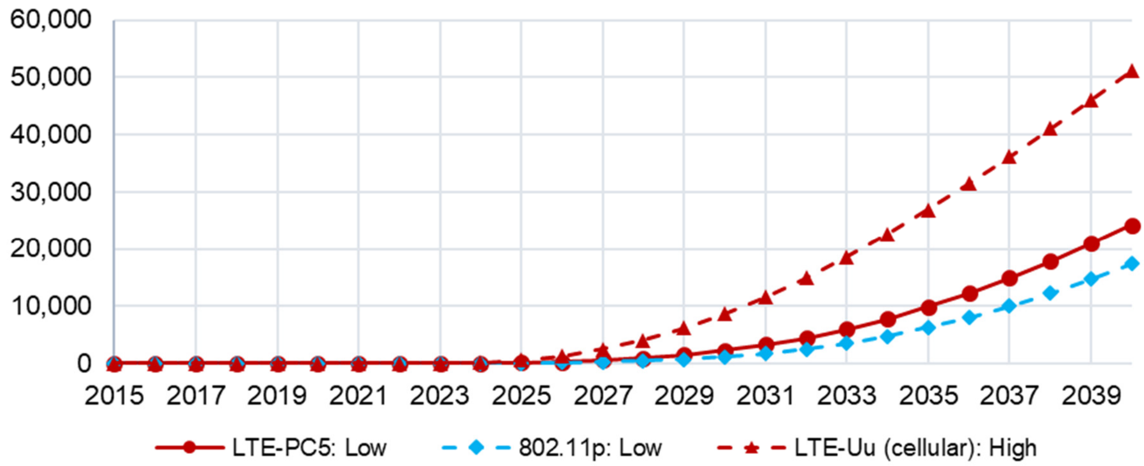
[2] 4 permanently disabling injuries such as damage to the brain or spinal cord, 8 serious injuries

Figure 1: Aggregated results for both use cases in the high scenario- Cumulative avoided fatalities and serious injuries - Without retrofitting



In the low scenario (see Figure 2), the direct communication solutions (LTE-PC5 and 802.11p) lie closer together in terms of cumulative avoided fatalities and serious injuries (24,242 and 17,401 in 2040 respectively), due to the assumption of zero uptake of these technologies in smartphones. LTE-Uu performance on the other hand is not facing the same technical barriers and shows significantly higher results with a cumulative number of 51,113 avoided fatalities and serious injuries in 2040. This is lower than in the high scenario due to the slower roll-out of the C-ITS communication solutions (particularly in the infrastructure).

Figure 2: Aggregated results for both use cases in the low scenario- Cumulative avoided fatalities and serious injuries - Without retrofitting



In summary, implementation of LTE-Uu (cellular) communication solution is shown, amongst the three communication solutions considered, to result in the highest benefits by 2040. This is due to the take up of this C-ITS communication solution happening faster than for other solutions in both the high and low cases considered, and it is enabled by the rapid penetration of the C-ITS communication solutions in cars and smartphones. In absolute terms, the benefit ranges from 3,932 to 8,774 avoided deaths across the EU by 2040, depending on whether the high case or low case assumptions are considered. It is worth noting that the absolute values are subject to various assumptions where sufficient data was not available (such as future geographic coverage and availability for LTE-Uu, alert reliability rates for direct communication in the V2I case, number of serious injuries avoided). Although the study team took great care to ensure all assumptions have been checked by industry experts and where possible, based on available data, these values should be treated with caution. Once further data becomes available these projections could be updated as necessary. Based on the assumptions outlined above, the comparison of C-ITS communication solutions remains valid and the relative impact of these solutions on safety in the use cases assessed in this study is likely to remain unchanged.

1 Introduction

1.1 Recap of previous 5GAA work

A previous 5GAA study [2] analysed the effectiveness of C–ITS using short-range direct communications to reduce the number of fatalities and serious injuries caused by motoring accidents in the EU. Specifically, LTE-V2X (PC5) and 802.11p direct communications technologies were compared for V2V services.

The study examined two independent scenarios: one where LTE-PC5 is the only deployed C-ITS technology, and another where 802.11p is the only deployed C-ITS technology. It should be noted that the same statistics and projection assumptions for road traffic fatalities were used across both studies.

To evaluate the reduction in the number of fatalities and serious injuries, additional assumptions in the following areas were made:

- The expected take-up (penetration) of LTE-PC5 and 802.11p among road users in the EU over time (including vehicles, motorcycles, bicycles and pedestrians), and
- The radio link performance of LTE-PC5 and 802.11p in successfully delivering actionable warning messages between road users in a number of collision scenarios.

These assumptions are unchanged across both studies for consistency (see Section 3.2 for more detail).

The study concluded that, overall, the deployment of LTE-PC5 would avoid greater numbers of fatalities and serious injuries on the EU's roads than would be the case for 802.11p. Specifically, the modelling undertaken showed that by the year 2040, 9,000 more fatalities would be avoided through the deployment of LTE-PC5 in the low scenario and 20,000 in the high scenario, than through the deployment of 802.11p.

By maintaining the major assumptions, this current report supplements the previous report on the two technical solutions previously studied with LTE-Uu (cellular), i.e. a network-based communications interface (Uu) operating in the traditional mobile broadband licensed spectrum.

1.2 Study objective and approach

Building on a previous study that Ricardo peer reviewed for 5GAA [2], the aim of this study is to explore EU road safety performance over time of different technical solutions for Cooperative Intelligent Transport Systems (C-ITS) communication. Three different technical solutions are defined and considered [4] [5]:

- Cellular vehicle-to-everything (C-V2X) communication which consists of two complementary communication modes, both based on the evolved LTE technology as defined by 3GPP (a global cellular specifications body), optimized it for automotive applications as defined in 3GPP Release 14 in 2017:
    - LTE-PC5: Communication solution that uses direct-mode communication between vehicles, road users and infrastructure operating in ITS bands (e.g. ITS 5.9 GHz) independent of cellular network;
    - LTE-Uu (cellular): Network-based communications interface (Uu) operating in the traditional mobile broadband licensed spectrum.
- 802.11p[3] (commonly referred to as DSRC and ITS-G5, in the US and Europe respectively), a Wi-Fi technology that supports Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) based on IEEE 802.11p. Similarly to LTE-PC5 it uses direct-mode communication operating in the ITS band of 5.9 GHz.

[3] the terminology has been kept in line with the previous Ricardo study

A key motivation for introducing Intelligent Transport Systems (ITS) is its major potential to improve road safety. Road safety is a major societal issue with 25,500 people having lost their lives on EU roads in 2016. While the statistics show that road fatalities have been cut by 19% over the last six years [6], these improvements might be still insufficient in meeting the EU's target of halving road fatalities between 2010 and 2020 as set out in the European Commission's Road Safety Programme 2011-2020 [7]. In particular, Cooperative ITS (C-ITS) has the potential to provide services that improve road safety and decrease both, the number and the severity of accidents.

For this study we have focused on two specific C-ITS use cases with high accident reduction potential that are on the European Commission's list of priority C-ITS services [1]. The selected services focus on vehicle-to-infrastructure (V2I) and pedestrian/cyclist to vehicle (V2P) communications.

- Red signal violation/intersection safety;
- Vulnerable Road User (VRU) protection.

The two use cases are priority services identified in the European Commission's 2016 European strategy on Cooperative Intelligent Transport Systems [1]. Being Day 1 and Day 1.5 services, which might generate a notification or a warning signal, they do not require any automated action by the vehicle. The driver always remains in control of the vehicle and thus remains liable. As long as the product is not proven to be defective, the liability is not expected to be transferred to the C-ITS enabled hardware manufacturer, service provider or network operator, as is set out in the Phase I report of the C-ITS platform [8].

Note that the three technical solutions are considered in isolation. This study does not therefore take account of any interoperability or compatibility aspects, but rather serves to illustrate the relative merits of each C-ITS communication solution considered in isolation. In practice, LTE-PC5 and LTE-Uu will complement each other as they utilise similar radio technology and chipsets. This is not reflected in this study.

The approach adopted was to obtain stakeholder inputs to help define the two use cases and to develop modelling assumptions. Stakeholders included 5GAA members (covering a wide range of companies from the automotive and information and communications technologies industries) as well as other European C-ITS experts. Through a similar modelling approach as applied in the 2017 5GAA study [2] the number of fatal accidents in Europe that could be avoided through the use of these C-ITS solutions was calculated.

The stakeholders who provided inputs to the development and definition of the use cases during this study are listed in Table 1.

Table 1: Stakeholders providing input to the study

Stakeholder	Stakeholder type
Compass4D	EU Implementation Project
C-Roads	EU Implementation Project
Honda	Vehicle Manufacturer (5GAA Member)
Ericsson	Telecommunications provider (5GAA Member)
Finnish Transport Agency and Finnish C-ITS deployment pilot in NordicWay2 project	Implementation project
Qualcomm	Communication Technology Provider (5GAA Member)
SWARCO	Traffic Signal System Supplier
Anonymous	Traffic Signal System Supplier
Deutsche Telekom	Mobile Network Operator (5GAA Member)

2 Definition of use cases

2.1 Red signal violation

To inform the development of this use case, consultations were held with representatives of different European C-ITS implementation projects[4] and with traffic signal system suppliers[5]. Furthermore, project documents (e.g. final reports) were reviewed from a range of implementation and research projects such as C-Roads, CODECS, CVIS, Intersafe, SAFESPOT, UR:BAN and Talking Traffic.

The results of this research indicated that whilst it is feasible to develop and/or implement traffic signal systems that can broadcast information on their status (red/green) and their expected time to the next change (particularly the change to red), there was no evidence of an ability to incorporate sensors and computing power (whether in the traffic signal unit or via “cloud” computing) for the unit to determine accurately whether an approaching vehicle would be likely to go through a red signal. This would require tracking individual vehicles and monitoring their position, speed and acceleration/deceleration on their approach to the traffic light; the input from the Compass4D project indicated that such measurements would not be accurate enough for this purpose. It was also noted that a vehicle that passes through a red signal will spend only a few seconds traversing the junction, which would require very low latency of the alert transmission and would give other drivers little time to react if an alert was transmitted once it was clear that a vehicle was going to pass a red signal. Concerns were also identified regarding the liability in the event of an accident occurring after an alert had been sent to other drivers. Broadcasting of alerts of signal violations to other drivers was thus not considered feasible. Therefore, from the lessons learnt through this research, combined with a consideration of what can be implemented in the modelling framework, the use case for red signal violation was defined as avoidance of accidents through alerts to approaching drivers (those at risk of violating signal). This use case is defined as follows:

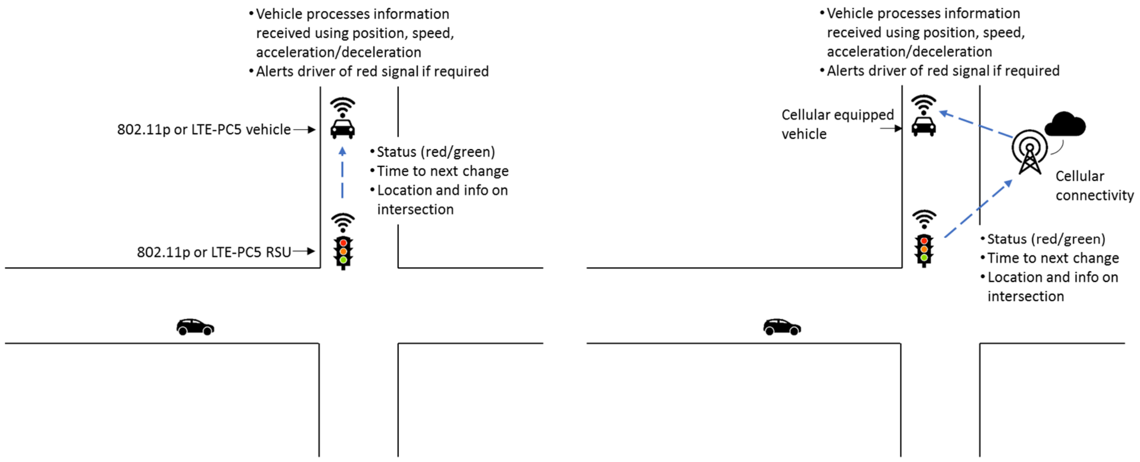
- Traffic lights (and/or management systems) are equipped with RSUs or cellular connectivity to enable one of the C-ITS communication technical solutions;
- The status (red/green) of the signal and the time to next change to red (if the current status is green) are transmitted to all vehicles in the vicinity. The signal also includes the location and information on the intersection structure, enabling a vehicle to determine its distance from the intersection (using the vehicle sensors to determine its own location);
- In the case of LTE-Uu connectivity, the information on the status and phasing of the traffic lights are disseminated via the cellular network, rather than a local broadcast signal.
- In-vehicle sensors and processing determine if the vehicle is likely to arrive at a red light too fast to stop (taking account of vehicle distance to stop line/point/area, speed acceleration/deceleration);
- The in-vehicle system may also include some predictive capability, based on the vehicles trajectory and other actions by the driver (e.g. the selection of a right turn indicator would indicate the intention to turn right at an intersection, which would be significant if the signal for turning right was red while that for turning left was green);
- If necessary, the approaching vehicle will alert its driver to start reducing speed;
- As a result, the driver of the approaching vehicle reacts by applying the brakes and the vehicle stops at the red signal, and the accident is avoided.

This use case is illustrated schematically in Figure 3.

[4] Compass4D, NordicWay2, C-Roads

[5] Anonymous, Swarco

Figure 3: Schematic illustration of red light violation use case for 802.11p / LTE-PC5 and LTE-Uu (cellular) connectivity



This use case builds on the green light optimal speed advisory (GLOSA) functionality by including the detection of a likely red light violation and alerting the driver. To allow the system to have beneficial impacts, it is important that drivers are only alerted when there is a significant risk that they will violate the red light unless they take additional action. Equally, it is important that drivers are alerted in sufficient time for them to take action to avoid violating the red light. To achieve this it will require the vehicle to have access to accurate information on its speed, acceleration/deceleration and distance from the intersection and accurate information on the signal timing. The latter will require low latency transmissions from the signal infrastructure to the vehicle to ensure that the information received (e.g. “the signal will change to red in 4.5 seconds”) is correct.

Some limitations on the effectiveness of the red light violation warning system were identified during the consultations with stakeholders and implementation projects. There is the potential that an alert of a potential violation might lead some drivers to accelerate (to attempt to cross the intersection before the change to red) rather than slowing down to stop at the red signal. Accurate information (i.e. alerts sent only when necessary) may assist in reducing this problem, although there may still need to be some training to reduce inappropriate responses. However, as with any information/warning-based service, the driver is fundamentally responsible for reacting to the alert in an appropriate manner. The specific design of the system and the application will also have an impact on this behaviour.

A further limitation identified is that the traffic signal management systems at some intersections can be localised (i.e. not part of a centralised management system) and can be highly dynamic, with only a short interval between the system “deciding” on the next change and the change in lights occurring. This may limit the time available for the vehicle to identify that it might violate a red light and to alert the driver. Such highly dynamic traffic light management occurs in particular countries (the Nordic countries were identified by the NordicWay project as having a widespread use of such systems) and in particular locations.

2.2 Vulnerable Road User protection

This use case is defined in line with the definition used in the previous 5GAA report on communication technologies for improved road safety in the EU [2]:

- VRUs are defined as pedestrians and cyclists. Motorcycles have not been classified as VRUs in this case, as they are modelled more in line with vehicles rather than pedestrians and cyclists;
- VRUs are assumed to be equipped with (i.e. will carry) smartphones with C-ITS communication solutions;
- Approaching vehicles will be alerted of VRUs in their vicinity. It is recognised that the exact manner in which information about nearby VRUs is prioritised and presented to the driver effectively could vary and may prove technically challenging. However, in the scope of this study,

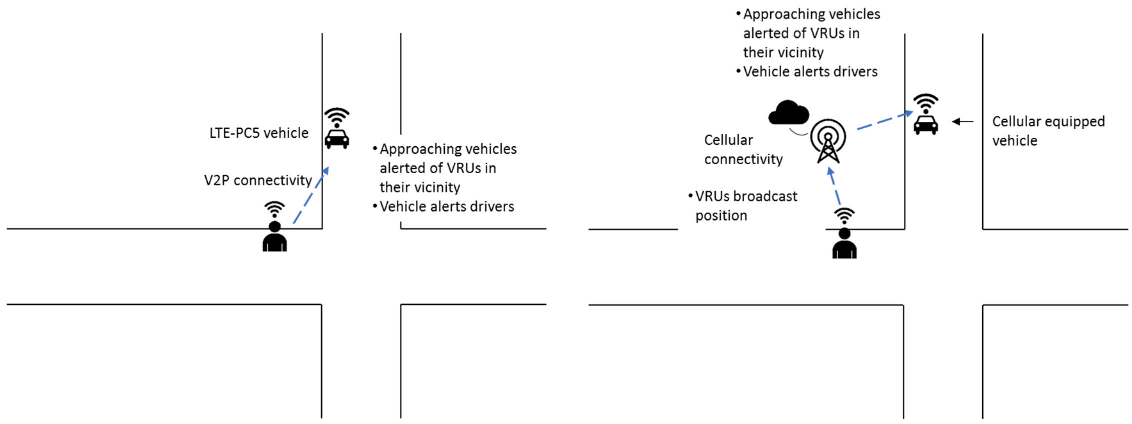
no assessment is made of the different possible methods nor judgement about their likely effectiveness. In this study it is assumed that a suitable technical solution will exist;

- Having been alerted, drivers may be able to avoid collisions with VRUs;

The use case does not include the VRU being informed of the presence of vehicular traffic, as the mechanism for, and the effectiveness of, the alert message is not clear. If included additional benefits could be provided.

This use case is illustrated schematically in Figure 4 on the following page.

Figure 4: Schematic illustration of VRU protection use case for LTE-PC5 and LTE-Uu (cellular) connectivity[6]



This use case is expected to have greatest effectiveness when the driver of the vehicle has difficulty in seeing the VRU from a distance and is travelling at a relatively high speed. For example, this may be because it is dark or because the VRU is around a bend in the road. In town and city centres, where there is a high density of pedestrians next to the road, traffic levels are likely to be high and vehicle speeds will be low with drivers probably being more aware of the nearby VRUs. Therefore, the likelihood of a fatal collision is likely to be lower. It is not the intention of this study to anticipate how alerts and user interfaces for such C-ITS applications may be developed and implemented but we assume that to avoid an excessively high level of false alarms, the systems that are made available will avoid alerts to the driver in such low vehicle speed / high VRU density situations.

The messages presented to the drivers will, therefore, be to alert them of the presence of VRUs of which they may not be aware. It is unlikely that the system will be able to provide warnings of sudden, unexpected movements by the VRU, due to the difficulty in monitoring their movements accurately enough and the latency associated with the information processing and transmission.

Although drivers may be alerted of the VRU presence, they may still not be able to avoid a collision due to difficulty in identifying appropriate avoidance actions or insufficient time available once they see the VRU (although the alert should enable them to start reducing speed or moving away from the kerb to reduce the probability of a collision). This will limit the ultimate effectiveness of the system.

These limitations on the effectiveness of C-ITS in the VRU use case are considered in this study using the effectiveness parameter in the modelling of impacts. This is described further in section 3.2.2.

[6] As explained later in section 3.2, 802.11p is not expected to be integrated in smartphones and thus will not be able to deliver the VRU protection service.

2.3 Retrofitting

In addition to the assumptions on the availability of integrated or embedded in-vehicle systems, the study also takes account of retrofitting cases by the drivers' use of smartphones with relevant applications installed.

For these retrofitting cases, it is assumed that some drivers will use popular third party (i.e. not provided by vehicle OEMs or telecoms companies) applications on their smartphone while driving, of which newer versions will include the safety-related features. Similarly to how drivers use their smartphones for satellite navigation purposes today, it is assumed that they will place their smartphone in a dashboard-mounted holder and that any alerts or other messages will be displayed to the driver via the smartphone screen (and any audible warnings will be sent through the smartphone speaker or via the vehicle speakers). In all other respects, the messages and alerts will take the same form as when provided through integrated systems.

The use of mobile phones within vehicles is already widespread, for both voice and information purposes. Although the metallic structure of the vehicle may lead to some loss of signal strength and GNSS reception, it is assumed that this will not be sufficiently detrimental to prevent the service from being usable. Therefore, the use of smartphones with safety-related applications may accelerate the deployment of the two use cases considered in this study, as they can be used in existing vehicles and those purchased in the near future without integrated cellular connectivity. This report identifies separately the impact of safety-related applications using smartphones as a retrofitting case from the main (integrated systems) cases.

A further case that has been considered for this study is the implementation of the safety-related functionality through a plug-in dongle or personal navigation device. Lack of data on how those other options could penetrate the market and their likely uptake, has been a barrier for modelling these cases. It is also assumed that, even if those other options are available, the smartphone would be a key component for most retrofit options.

Regarding the technical feasibility of integrating C-ITS solutions in smartphones, issues such as high costs for high-precision positioning and high power consumption are considered for each technical solution individually. In particular a "position accuracy" demanding use case such as VRU protection might be affected.

3 Modelling framework and key assumptions

3.1 Modelling framework

The modelling framework employed is the same as that from the previous Ricardo peer-reviewed study [2], adapted to reflect the inclusion of LTE-Uu (cellular) and V2I/V2P communication instead of V2V. The primary calculation derives the number of avoided fatalities as a function of time as:

$$N_{Avoid}(t) = N_{Base}(t)P_{C-ITS}(t)F_{Mit}D_{C-ITS}\,E$$

In this formula:

- $N_{Avoid}\,(t)$: number of fatalities or serious injuries that can be avoided in year t.
- $N_{Base}\,(t)$: baseline number of fatalities or serious injuries that would occur in year t in the absence of C-ITS technologies.
- $P_{C-ITS}\,(t)$: likelihood in year t that any two ITS stations (vehicles, VRUs, RSUs,) involved in a potential accident will be equipped with C-ITS communication solution allowing V2X communications.
- F_{Mit}: fraction of fatalities or serious injuries which can be addressed and mitigated by the considered C-ITS communication solution. This factor is maintained constant in time and the same for all three technical solutions.
- D_{C-ITS}: alert/warning delivery reliability: i.e., the likelihood that data transmitted from an ITS station via a C-ITS communication solution is successfully communicated to its intended recipient. This factor differs for the three technical solutions[7].
- E: effectiveness of a received alert/warning message in appropriately affecting the behaviour of the driver of a vehicle travelling towards a potential accident. This factor is maintained constant in time and the same for all three technical solutions. The values used for the modelling of the effectiveness of alert signals in this report are obtained from the Drive C2X study where the analysis from a real-life piloting test was carried out [9]. The effectiveness of the HMI is not taken into consideration in this model, as the same type of alert is assumed to be delivered for all the three technical solutions.
- Components that are variable over time are marked with a (t), except for DC-ITS where a different approach is adopted for different technical solutions (see footnote 7).

3.2 Key assumptions

The following section presents the input assumptions to the modelling. Where literature was available and used to support the assumptions, it has been cited throughout. Some of the presented future projections have been based on expert judgement and have been verified through three rounds of discussions with the 5GAA board members and individual stakeholder input through data requests. To reflect uncertainties in the assumptions, high and low scenarios have been developed for some of the input parameters. Full details on the used assumptions can be found in Annex A - Assumptions.

3.2.1 Red signal violation

3.2.1.1 Accidents baseline

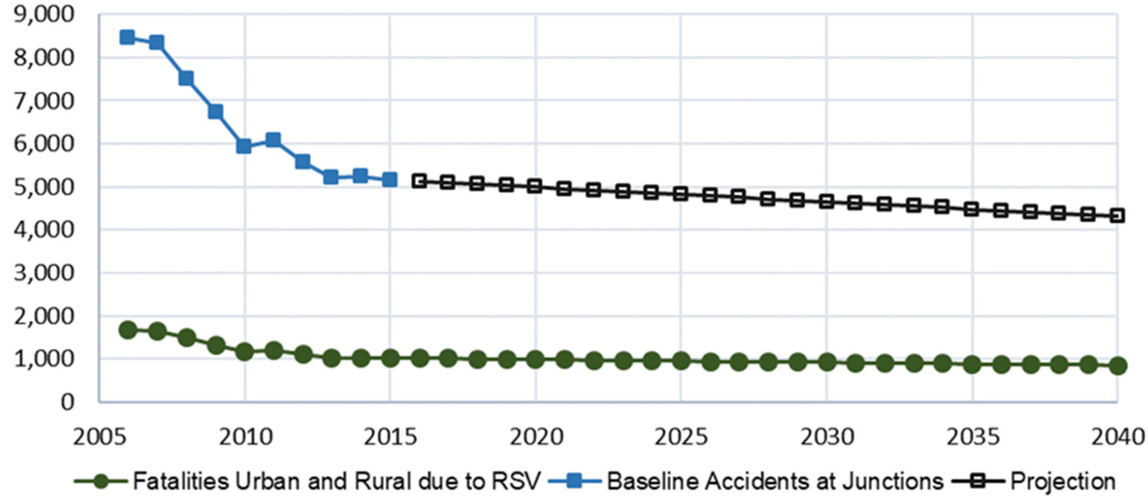
Based on data from the European Road Safety Observatory [9] on the number of accidents at junctions, the baseline for intersection safety was derived as a number of fatalities at junctions across the EU in 2015, which were then projected to 2040 by linear extrapolation from the last three years. It

[7] For LTE-PC5 and 802.11p the delivery reliability rates (DRS) are kept constant in time, nevertheless it is recognised that technological improvements might impact on the DRS, however, this aspect has not been modelled due to unavailable information. For LTE-Uu, the DRSs include data on coverage and availability of the mobile signal, and, in this case, projections have been considered. Therefore, the value is time dependent.

was assumed that 20% of the accidents at junctions were due to red signal violations. This assumption was derived following a review of available literature on causes of accidents at junctions. A report by Morgan Stanley Research [10] provides information on the causes of fatal accidents in the US. By dividing the percentage of accidents due to failures to obey traffic signals by the total percentage of accidents that related to issues at junctions, a value of approximately 20% was obtained. This was supported by another study [11], which notes that in 2000, 20% of vehicles involved in fatal accidents at signalised junctions (in the US) failed to obey the signals. Due to the lack of similar data for Europe, the US value of 20% was adopted for this study. We acknowledge that the actual numbers for the EU could differ; however, the same accidents baseline underlies the analysis for the different technical solutions, and any performance comparison will be unaffected.

The extrapolation of the fatalities data gives a baseline reduction in accidents between 2015 and 2035 of approximately 15%; see Figure 5. The total numbers of accidents for the baseline case are presented in Annex A - Assumptions, Table 3.

Figure 5: Recorded fatalities at junctions in Europe (EU28) and projections to 2040; calculation of fatalities due to red signal violations (RSV)



Source: Eurostat data and Ricardo analysis

3.2.1.2 Penetration rates

Vehicle connectivity

The penetration rates for C-ITS communication technical solutions in new vehicles were derived as follows:

<u>LTE-PC5 and 802.11p</u>

- The penetration rates for LTE-PC5 and 802.11p were obtained from the previous Ricardo study [2] (low and high penetration scenarios) and can be found in Annex A - Assumptions, Table 4.

<u>LTE-Uu (cellular):</u>

- The starting point for the penetration rates for LTE-Uu (cellular)-equipped vehicles was based on existing industry data [12], [13], [14] on cellular connectivity indicating that world-wide 55% of new vehicles in 2020 will be equipped with cellular connectivity. As a conservative estimate, the same value has been applied for the EU.
    - Under the high scenario, it was assumed that the addition of LTE-Uu (cellular) capability and related C-ITS services in a vehicle can be achieved via a software update. Therefore, once C-ITS services become available (from 2019) all new vehicles with LTE-Uu (cellular) connectivity will be enabled with LTE-Uu (cellular) capability and related C-ITS services in within a year. This scenario relies on the assumption that all new vehicles with cellular connectivity will have a suitable dashboard functionality to provide the information to the driver. It is assumed that 100% of new vehicles would be equipped by 2022.

- Under the low scenario, the penetration of LTE-Uu technical solution (including C-ITS functionality) was assumed to follow a similar uptake trend of LTE-PC5, however an annual uplift of 5% has been introduced to reflect the fact that cellular would only require a software update and not hardware like LTE-PC5. More details on the communication solution penetration rates for the LTE-Uu case can be seen in Annex A - Assumptions, Table 4.

Figure 6 to Figure 8 show the penetration rates used for the three communication solutions under the low and high penetration scenarios.

Figure 6: Modelled penetration rates for LTE-PC5 in new vehicles

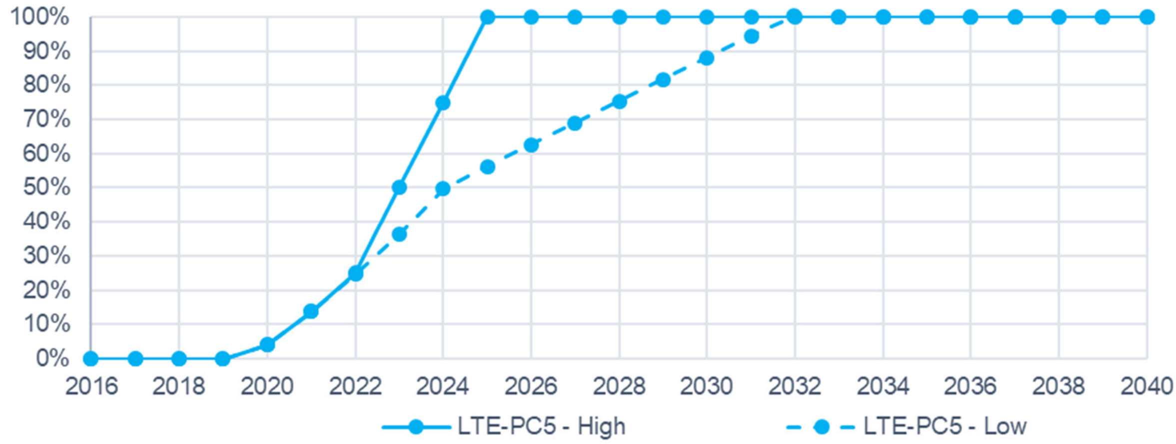


Figure 7: Modelled penetration rates for 802.11p in new vehicles

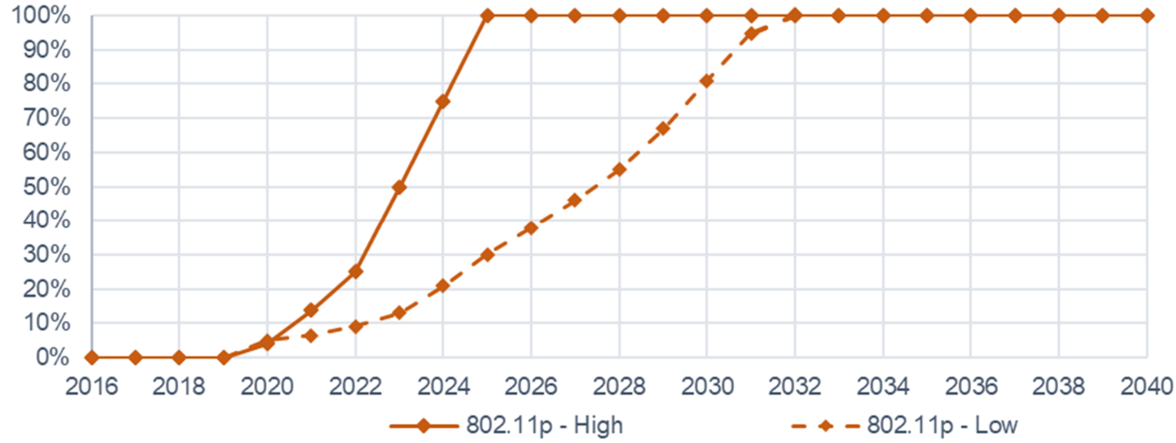
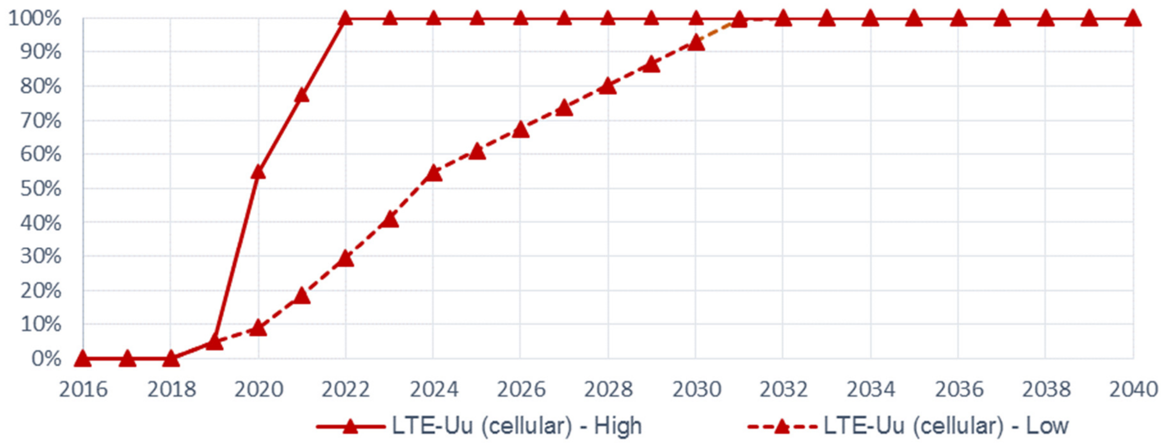


Figure 8: Modelled penetration rates for LTE-Uu in new vehicles



Smartphone applications - Retrofitting

In the red signal violation use case it is assumed that existing vehicles could be retrofitted through smartphones to deliver V2I services. While there are other devices (e.g. personal navigation devices and plug-in dongles) that would potentially allow retrofitting, this study only focuses on smartphones due to lack of data on how those other options could penetrate the market and their likely uptake. It is also assumed that even if those other options are available, the smartphone would either be a key component for most retrofit options or by far the dominant option. These retrofitting assumptions are in line with European Commission work on C-ITS [15]. The efficiency of these systems will depend on the evolution of positioning and latency improvements. This will bring a higher efficiency, which however has not been modelled in this study.

The penetration rates for retrofitting of existing vehicles with C-ITS communication solutions through smartphones were derived considering the following points:

802.11p:

- Based on a comprehensive literature review and inputs from industry experts, it is not expected that 802.11p communication technologies will be fully integrated in smartphones, regardless of whether it is used for retrofitting of vehicles or in VRU protection applications. While there have been trials in the US on dedicated short-range communication (DSRC) technology in smartphones (e.g. trial by Honda and Qualcomm [16] or the Arizona Connected Vehicle Test Bed, Tampa Hillsborough Expressway Authority (Florida) [17]), the feasibility of 802.11p in smartphones for C-ITS communication could not be demonstrated. Consultation with 5GAA members (including Honda and Qualcomm) as part of this study highlighted that there are still technical barriers to the integration of 802.11p into smartphones such as high costs for high-precision positioning and high power consumption. While the evolution of positioning solutions will likely address the first challenge, the second prevents the integration of 802.11p into smartphones and thus, it is unlikely that smartphones will have this capability for retrofitting in vehicles. Research done by 3GPP shows that a power-efficient sensing scheme, i.e. partial sensing, in LTE-PC5 would balance the radio performance and battery consumption for UE devices that have limited battery capacity [18][19], and thus be more favourable to V2P scenarios than the frequent medium sensing required in CSMA of 802.11p. 5GAA members also highlighted that most existing Wi-Fi chipsets cannot support 802.11p. In order to do so, a handset manufacturer would have to adapt existing Wi-Fi chipsets to support 802.11p in addition to normal Wi-Fi (which will likely result in extra cost, e.g. in terms of re-certification). Furthermore, ITS-G5 might require complex mode changes between 802.11p operation and standard Wi-Fi operation.
- Given the constraints outlined above, the penetration for 802.11p in smartphones is assumed to be zero.

LTE-PC5:

- In the high scenario the start date for penetration is assumed to be 2022[8], which is when the LTE-PC5 chip will become available for smartphones. The speed with which LTE-PC5 could be rolled out is based on the assumption that it takes 6 years for the LTE release 14 to penetrate all chips (in line with assumptions in the previous study [2]).
- In the low scenario LTE-PC5 penetration is assumed to be zero, in line with 802.11p communication technologies to reflect uncertainties around C-ITS hardware integration in smartphones.

LTE-Uu (cellular):

- In the high scenario for the cellular case, it is assumed that C-ITS functionality can be rolled out in all available smartphones commencing from 2019 through a software update; first significant penetration is then seen in 2020, with maximum penetration achieved in 2022[9].
- In the low scenario for the cellular case, the same start year (2022) and speed of deployment (six years to maximum penetration) are assumed as for the high scenario LTE-PC5 case.

[8] based on 5GAA member input

[9] Expert judgement, verified through 5GAA member input

The start date of 2019 for the high scenario is based on the Memorandum of Understanding between CAR 2 CAR Communication Consortium and the C-Roads Platform on joint deployment of C-ITS by 2019 [20].

Regardless of which C-ITS communication solution is considered, in addition to the penetration of C-ITS functionality in all smartphones, the percentage of drivers with access to a smartphone was considered, based on the population age distribution [21]. In line with the previous study [2] we assume for smartphone ownership among drivers that only a percentage of the population aged 80 or older will use smartphones. It is observed that 17% of the population aged 80 or older use a smartphone in 2016 [22] with the percentage linearly increasing to 31% in 2024 and 59% in 2029 (this value is then kept constant for future years). This is to account for the fact that people will keep using the smartphone when they get older. The minimum age of a driver was taken as 18 years, so no minimum age threshold (for smartphone users) was applied. For drivers below 80 years of age, the percentage of smartphone ownership is projected out to reach 100% by 2021, following historic trends from literature [23] [24]. Furthermore, it was recognised that not all users will use the service, even when available (e.g. due to concerns over data privacy). The modelled penetration of C-ITS functionality therefore has been capped at 90% as it is assumed that some users will not wish to use the service even if it is available and technical communication solution exists. This value has been developed together with 5GAA member input.

The penetration rates used in the retrofitting scenario are calculated by multiplying the penetration rates of the communication solution (i.e. LTE-PC5 or LTE-Uu) in smartphones owned by drivers with the cumulative fleet of retrofittable vehicles. The number of drivers owning a smartphone with the considered C-ITS communication technical solution is evaluated considering the stock of new smartphones, based on the total penetration rate of smartphones among the EU population in combination with a stock model for smartphones based on a 2-year lifetime and consideration of EU population age as mentioned above. The number of retrofittable vehicles is calculated by subtracting the number of new vehicles assumed to be already equipped with a technical solution from the total fleet, thus obtaining the number of vehicles in the fleet which do not have the considered C-ITS communication technical solution.

The total retrofitting penetration rates P(t) across the entire vehicle fleet are calculated by dividing the cumulative number V_{ret} (t) of retrofitted vehicles by the total size V(t) of the projected vehicle fleet, i.e.;

$$P(t) = \frac{V_{ret}(t)}{V(t)} = \frac{U_{ret}(t) * D(t)}{V(t)}$$

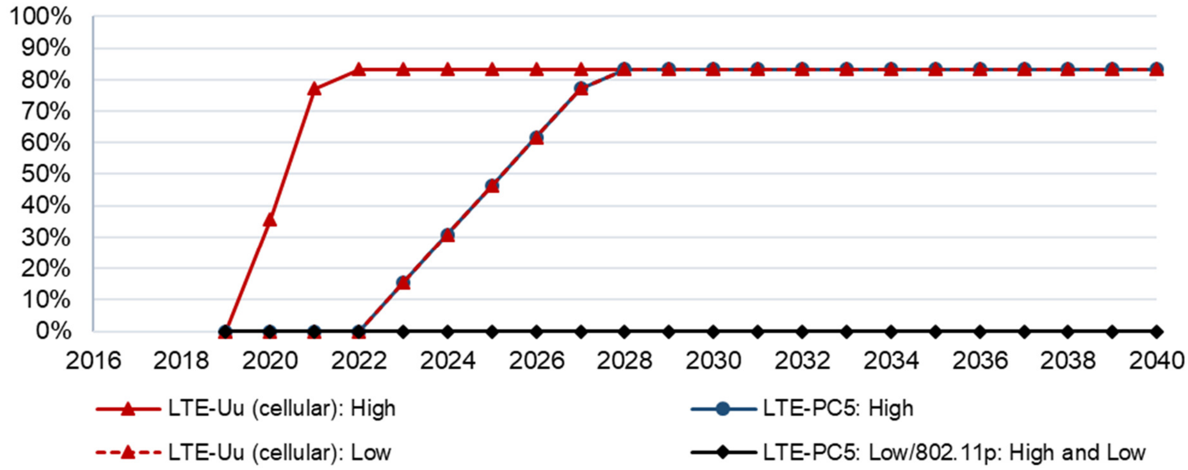
Where U_{ret} (t) is the number of retrofittable vehicles in year t and D(t) is the number of drivers owning smartphones equipped with C-ITS functionality.

To this end, in the retrofitting scenario, the total penetration in vehicles is given by two components, the penetration in retrofittable vehicle $P(t)$ above, plus the penetration in new vehicles.

The penetration rates for retrofitting can be found in Annex A - Assumptions, Table 5.

Figure 9 shows the penetration rates for smartphones owned by drivers assumed for the red signal violation case. A cap is reached by 2024 considering limitations in uptake due to population age and user decisions on the use of C-ITS functionality if available. Detailed plots for C-ITS functionality uptake for each individual communication solution are shown in Figure 28 in Annex A - Assumptions.

Figure 9: Modelled penetration rates for LTE-PC5, 802.11p and LTE-Uu (cellular), for the vehicle retrofit case



Infrastructure

The penetration rates for C-ITS communication solutions in infrastructure were derived considering that traffic lights (and/or management systems) are either equipped with LTE-PC5, 802.11p, and/or connected to a traffic management system that is able to provide the necessary information over the cellular network (through LTE-Uu) to enable one of the C-ITS communication technical solutions.

Literature research and discussions with experts (e.g. deployment project contacts) has shown that there are strong barriers to authorities equipping traffic lights with RSUs or cellular connectivity, due to high costs and a lack of a business case. While there are some examples for connected traffic lights from the Netherlands and in China, the number of traffic lights connected to central management systems (i.e. Control Centres) is low in Europe, and those that are connected (at least in the UK) are not actively managed all the time (e.g. just at peak periods). It was also found that there is currently limited experience of connecting traffic lights to a cellular network. Given the lack of information on connecting infrastructure to cellular networks for C-ITS services, the same infrastructure penetration rates are assumed for all three technical solutions.

The modelling of RSU uptake has been derived from work that Ricardo conducted on C-ITS for the European Commission [15]:

- RSU uptake in urban regions has been based on assumptions of a lifetime for traffic lights of 12.5 years and 75% of newly installed traffic lights being equipped with RSUs with one of the two direct technical communication solutions (LTE-PC5 and 802.11p). For connected traffic lights in the LTE-Uu case, the same uptake rates are used.
- RSU uptake in traffic signals on rural roads has been based on an analysis of current deployment of RSUs in Europe's road network and has been projected out to 2040 assuming constant uptake rates. As current deployment is primarily limited to the TEN-T network, the penetration rates for non-motorway rural roads have been calculated as 25% of the uptake rate in TEN-T corridors. Again for LTE-Uu, the uptake rates for connected traffic lights are assumed to be the same as for RSUs.
- Differentiation of penetration for the high and the low scenarios is based on current and planned actual deployment in advanced countries (used for the high scenario) and countries with medium progress (used for the low scenario).

The penetration rates for infrastructure for C-ITS services in urban and rural areas are shown in Figure 10 and Figure 11, the penetration rates can also be found in Table 6 in Annex A - Assumptions.

Figure 10: Penetration rates for roadside units at traffic signals in urban areas (all three technical solutions)

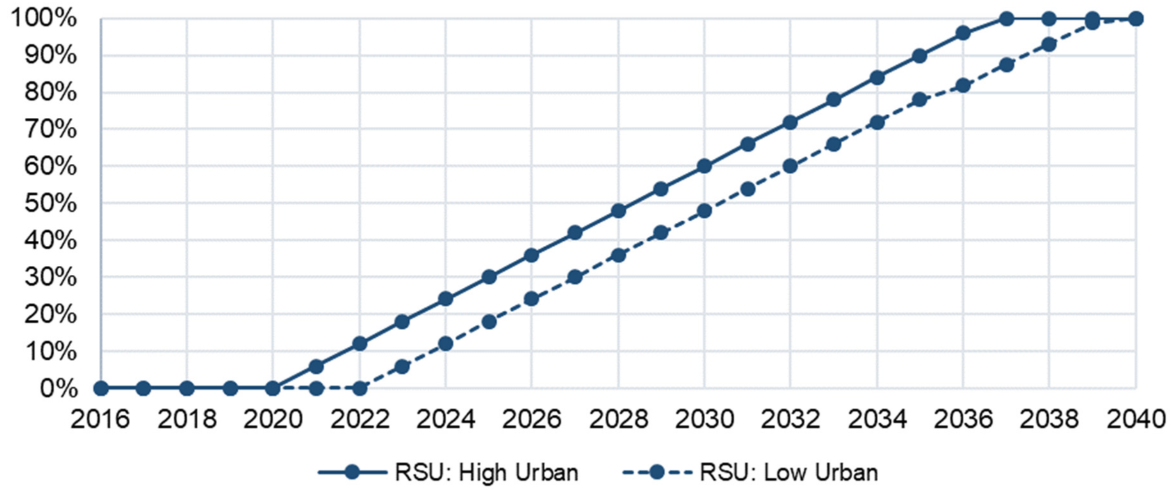
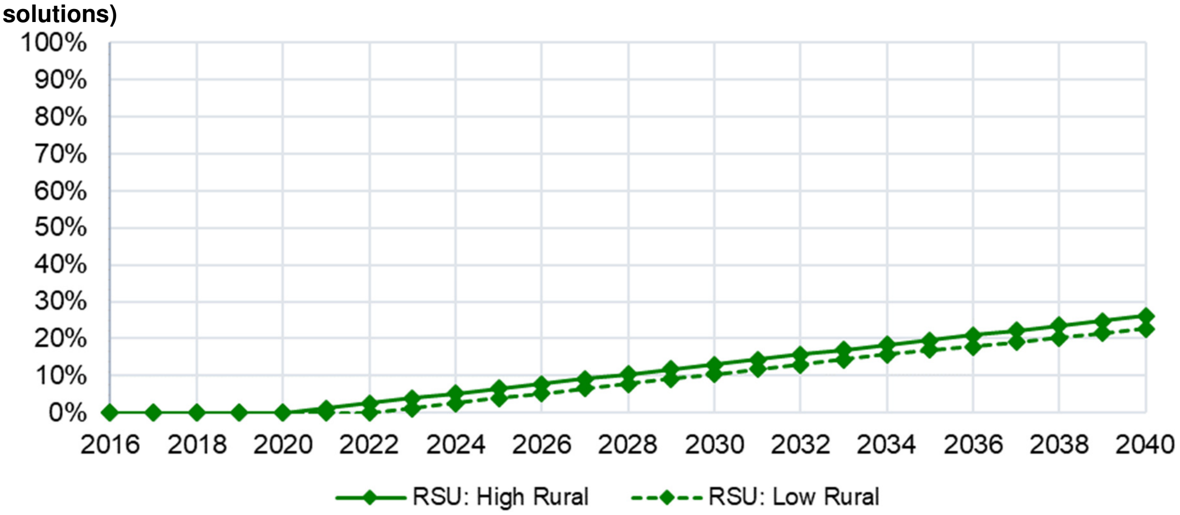


Figure 11: Penetration rates for roadside units at traffic signals in rural areas (all three technical solutions)



3.2.1.3 Alert delivery rates

For safety-related C-ITS services to be successful, it is necessary for the alert to be received by the relevant person (usually the vehicle driver) in sufficient time[10] to allow action to be taken to avoid a potential collision. These alert delivery rates are assumed to be the same regardless of whether the technical solution is manufacturer-fitted (built into the vehicle) or retrofit (through a smartphone). The modelling of the potential to avoid the collision takes account of the following aspects of the delivery of the alert, for each technical solution:

802.11p and LTE-PC5

Alert delivery reliability is the likelihood that a C-ITS warning message transmitted from one road user will be successfully received by the other ITS devices (vehicles or infrastructure). The alert delivery rates are based on the 3GPP [25], model, as used for the previous study (see Table 2). For more details on the 3GPP modelling, please refer to Annex B - Alert delivery reliability from 3GPP model.

[10] In the RSV scenario a speed range between 15km/h – 40km/h has been used to evaluate an average alert delivery rate on urban roads. This implies that the signal is received by the driver within 13 metres from the traffic light, if the speed is 15km/h or, within 46 meters from the traffic light if the vehicle is proceeding at the highest speed. For rural junction a speed range between 50km/h (i.e. 63m) and 80km (i.e.130m) has been used. The same assumptions have been used both for LTE-PC5 and 802.11p.

Although some differences in alert delivery rates might be expected from the previous model due to the different situations and different C-ITS applications (e.g. V2I communication instead of V2V), the modelling used the same values. To check the impacts of this assumption, sensitivity analyses of alert delivery rates were performed. It is most likely that the actual alert delivery rates would be higher for the V2I scenario. For the sensitivity analysis the alert delivery rates were thus set to 100%, which resulted in a change in saved fatalities of 2% for LTE-PC5 and 8% for 802.11p in 2040[11]. These results showed that the impact of changes in the alert delivery rates is relatively small, thus no additional modelling through the 3GPP model was carried out.

Table 2: Alert delivery rates – 802.11p and LTE-PC5

	At junction		Not at junction	
	Urban	Rural	Urban	Rural
V2Pedestrian – 802.11p	78.00%	58.60%	74.80%	96.50%
V2Pedestrian – LTE-PC5	95.70%	67.30%	88.37%	98.40%
V2Vehicles – 802.11p	78.00%	65.70%	80.70%	98.00%
V2Vehicles - LTE-PC5	95.70%	82.50%	95.59%	99.37%

<u>LTE-Uu (cellular):</u>

An equivalent alert delivery factor was developed based on cellular coverage, (service) availability and reliability of signal. Thus, for LTE-Uu (cellular) the factor that can be compared with the alert delivery rate for LTE-PC5 and 802.11p and corresponds to the alert delivery ($D_{C\text{-ITS}}$) factor in the main formulas is:

$$D_{C-ITS\ (\mathrm{LTE\_Uu})} = \mathrm{C}\ (\mathrm{t}) * \mathrm{A}(\mathrm{t}) * \mathrm{Dr}$$

Where:

- C(t) is the European average geographical cellular coverage in urban or rural area in a given year;
- A(t) is the European average service availability in urban or rural area in a given year, i.e. the likelihood that the user is able to use the service once he has signal;
- Dr is the reliability of delivering the signal.

Only 4G coverage and availability were considered due to the lack of information on 3G and 5G; thus the assumptions made here are conservative. Uncertainties in coverage and availability were covered through high and low scenarios

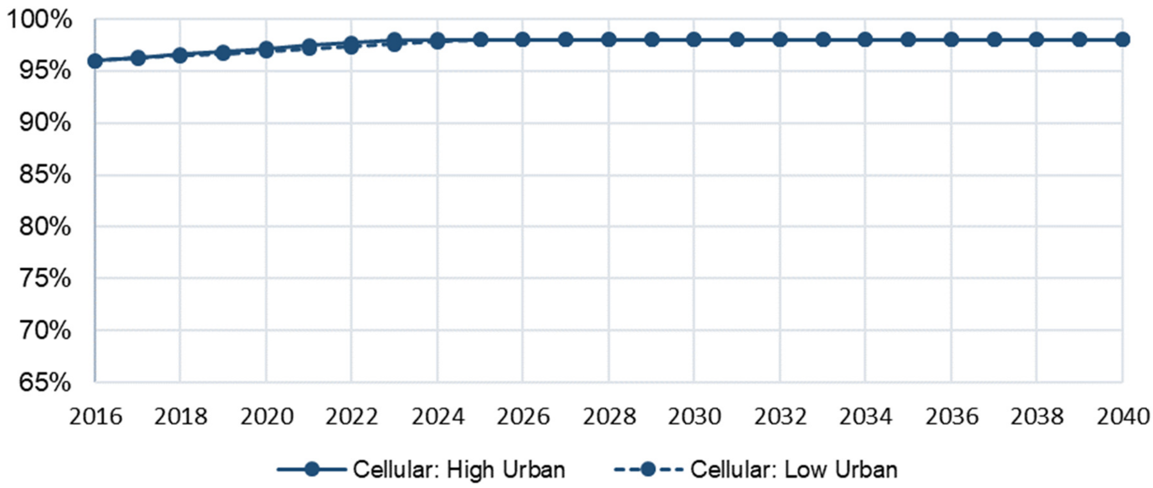
- Geographic coverage:
    - Current values for geographical coverage were based on 2016 data published by the European Commission [26] and by OpenSignal [27];
    - In the urban case it is assumed that maximum coverage is reached from 2016 in 7 years (high) and 9 years (low) in a linear projection. This was an assumption developed with 5GAA members.
    - In the rural case it is assumed that maximum coverage is reached from 2016 in 7 years (high) and 9 years (low), in line with the assumptions for the urban case;
    - Maximum coverage was assumed to never reach 100% to reflect a realistic scenario that takes into account technical barriers for full coverage. The caps for coverage were set at 98% for urban and 95% for rural.

[11] For the VRU protection case the change in avoided fatalities by 2040 is 3% for LTE-PC5. 802.11p is not able to deliver any fatalities reductions as discussed in section 3.2.2.

- Availability (available bandwidth):
    - Current values for availability were based on 2016 data published by the European Commission [26] and by OpenSignal [27];
    - In the urban case it is assumed that maximum availability is reached in 12 years (high) and 15 years (low). These projections were developed through verification by 5GAA members.
    - In the rural case it is assumed that maximum availability is reached in 8 years (high) and 10 years (low). This has been verified through 5GAA input.
    - The caps for availability were set at 95% for both coverage and availability.
- Reliability of signal was assumed to be 99% based on 5GAA modelling[12]. The work provides reliability rates for different scenarios using Cooperative Awareness Messages (CAM) at 5 to 10 Hz. Depending on the scenario the reliability rates range between 95% and 100%. Given that this study only considers Decentralised Environmental Notification Messages (DENM), the actual network loads will be smaller than for the modelled scenario. Furthermore, a single 10MHz carrier was considered for the 5GAA modelling, which is a conservative assumption for any MNO. Background traffic is considered and a first-in-first-out (FIFO) approach was used in the scheduler without Quality of Service (QoS) traffic differentiation. Higher reliability could be achieved in the presence of a QoS policy; however, this was not explicitly considered. In effect this means that the 5GAA modelling results are conservative considering the scenarios modelled here, thus this study assumes a 99% reliability rate, at the upper end of the assessed range.

The development of geographic coverage and availability over time are shown in Figure 12 to Figure 15. Full tables on the coverage and availability used for the modelling can be found in Annex A - Assumptions, Table 8 and Table 9.

Figure 12: Geographic coverage of 4G signal in urban areas



[12] based on 5GAA modelling, not publicly available yet

Figure 13: Geographic coverage of 4G signal in rural areas

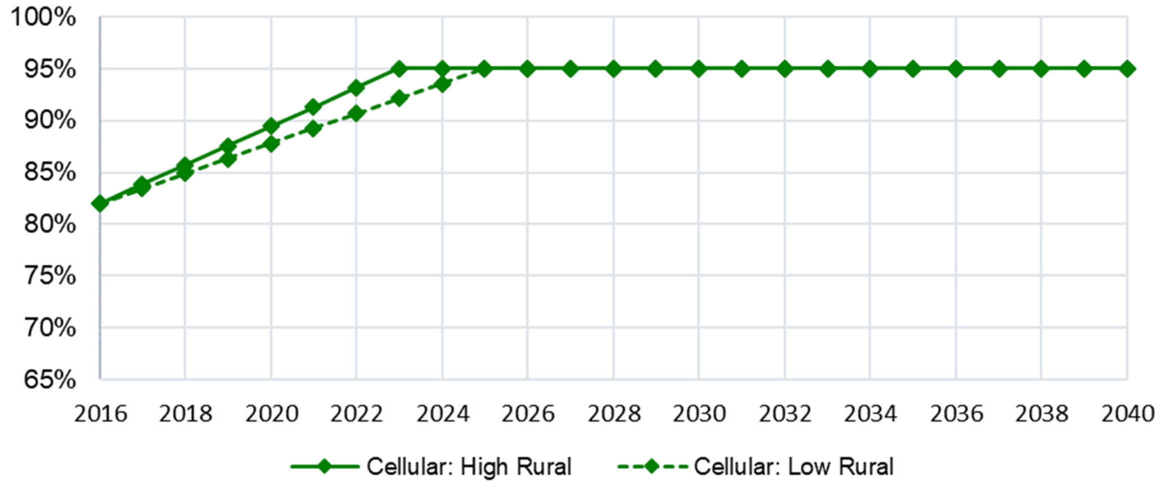


Figure 14: Availability of 4G signal in urban areas

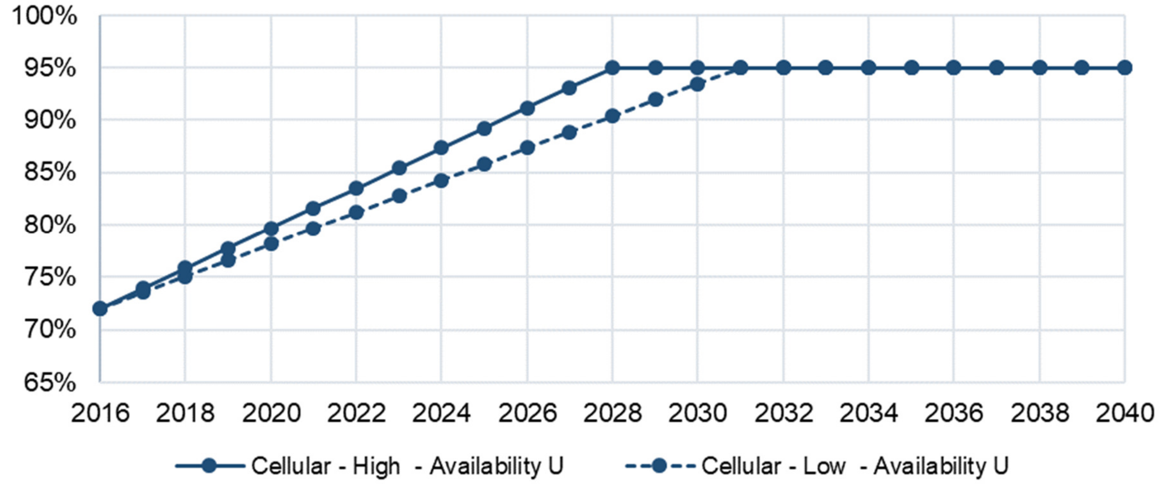
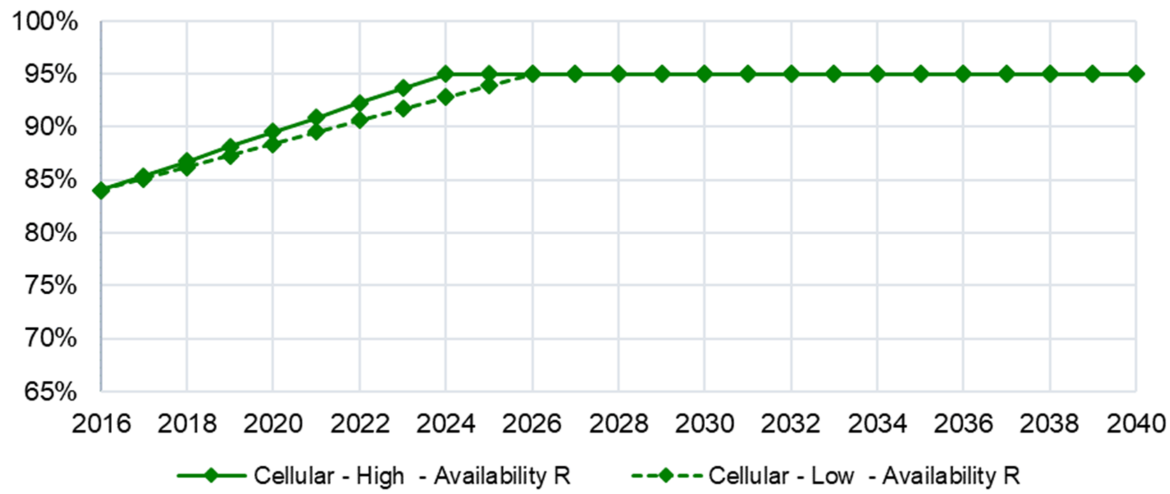


Figure 15: Availability of 4G signal in rural areas



3.2.1.4 Fraction of fatalities that can be mitigated

The proportion of fatalities which cannot be addressed or mitigated through the use of C-ITS solutions must be considered. Accidents with all road user types can be addressed through red signal violation C-ITS services, except those which involve drivers whose ability to control the vehicle and react to commands is impaired, e.g. if they are under the influence of drugs or alcohol. The percentage of accidents that can be addressed through C-ITS is assumed to be 82% of all accidents involving a vehicle [28]. Note this does not mean that C-ITS will be 100% effective in preventing the accident from occurring. This is essentially the upper boundary for the number of accidents that could potentially be prevented by C-ITS.

3.2.1.5 Effectiveness of a received alert/warning message in appropriately affecting the behaviour of the driver

Even for cases in which the driver is not impaired, not all accidents that could, in principle, be avoided will be. The failure to avoid an accident may be associated with driver distraction (and, hence, their perception of the alert) or their reaction to the alert when it is recognised. The modelling, therefore, considers this limitation through a further factor representing the effectiveness of the alert in producing the required response from the driver. It is assumed that the mechanism by which the alert is transmitted (e.g. screen image and/or audible warning) will be the same, whether it is produced by a manufacturer-fitted system or a retrofitted smartphone system. Therefore, the effectiveness factor is independent of the system used to transmit the alert.

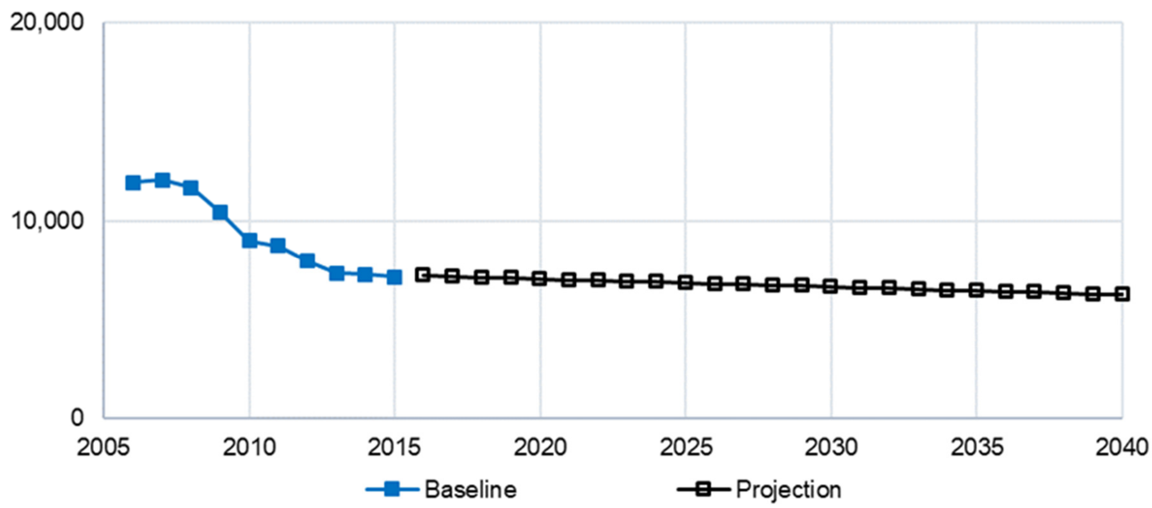
The effectiveness of warning messages on driver behaviour has been examined in the DRIVE C2X study [29] as a function of the mode of transport and road type. The data indicates that the effectiveness of a warning message in avoiding accidents which occur at junctions ranges from 65% for urban roads to 68% for rural roads. These values were used in our modelling of both the red signal violation and VRU protection use cases.

3.2.2 VRU protection

3.2.2.1 Accidents baseline

For the VRU protection baseline, a similar approach was adopted to that for the red signal violation case. The total fatalities in EU roads have been projected to 2040 based on linear extrapolation from the last two years of recorded data; see Figure 16. All fatalities of pedestrians and cyclists, whether at junctions or not, have been considered in the study based on a split by mode obtained from Eurostat data. See Table 3 in Annex A – Assumptions for the case data.

Figure 16: Total recorded VRU fatalities and projection to 2040



Source: Eurostat data and Ricardo analysis

3.2.2.2 Penetration rates

Vehicle connectivity

The penetration rates for C-ITS communication solutions in new vehicles were the same as for the red signal violation case (see Section 3.2.1.2).

Smartphone applications - Retrofitting

The penetration rates for retrofitting C-ITS functionality in smartphones in vehicles were the same as for the red signal violation case (see Section 3.2.1.2).

Smartphone applications - VRU application

For VRU protection services to be delivered, it is assumed that VRUs will be equipped with smartphones. In line with the assumptions on retrofitting, in our calculations for the penetration of VRU C-ITS functionality in smartphones we considered: C-ITS communication solution penetration, proportion of the population equipped with smartphones and how likely the VRU is to use the service if available, i.e. penetration for the VRU application, taking into account battery drainage or data privacy concerns.

The penetration rates for C-ITS functionality through smartphones for VRUs were derived considering the following specific points:

<u>802.11p:</u>

- For the same reasons as explored in the retrofitting scenario for the red signal violation use case, 802.11p penetration in smartphones is assumed to be zero.

<u>LTE-PC5:</u>

- In the high scenario the initial roll-out of the C-ITS communication solution in smartphones using LTE-PC5 is assumed to start in 2022, when the LTE-PC5 chips are expected to become available in smartphones (in line with the red signal violation use case). Full penetration will be reached after 6 years based on the assumption that it takes that long for the LTE release 14 to penetrate all chips (in line with assumptions in previous study [2]).
- In the low scenario LTE-PC5 penetration is assumed to be zero, in line with 802.11p communication technologies to reflect uncertainties around C-ITS hardware integration in smartphones.

<u>LTE-Uu (cellular):</u>

- In the high scenario for LTE-Uu, it is assumed that C-ITS functionality can be rolled out in all available smartphones commencing from 2019 through a software update; significant penetration is then first seen in 2020, with maximum penetration being achieved in 2021[13].
- In the low scenario, a delay is assumed in the start year for VRU protection services, compared to the red signal violation case. This is because VRU protection is considered a Day 1.5 service. While roadmaps for Day 1.5. services consider these to come to the market around 2025 [8], we assumed the delay to the roll-out is partially reduced because there have already been trials of Bluetooth-based traffic alerts for pedestrians [30] and the technical feasibility of such services was considered to be high by 5GAA members. Thus the start date was delayed from the red signal violation case to start in 2022, with maximum penetration being achieved in 2027.

In the context of VRU protection, we assume that (a) citizens aged 12 or younger will not have access to a smartphone; and (b) only a percentage of the population aged 80 or older will use smartphones. In relation to (b), we assume that 17% of the population aged 80 or older use a smartphone in 2016 [22] with the percentage linearly increasing to 31% in 2024 and 59% in 2029 (this value is then kept constant for future years). This is to account for the fact that people will keep using the smartphone when they get older.

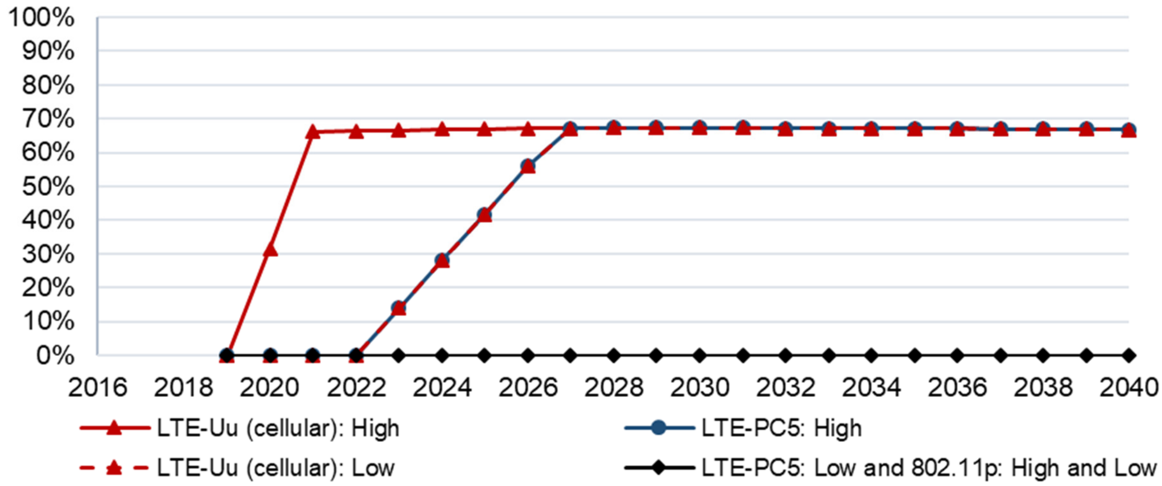
To account for the fact that not all users will likely use the service, a cap of 80% was applied. This is lower than in the retrofit case for red signal violation because it is assumed that concerns over battery

[13] Expert judgement, verified through 5GAA member input

life and personal safety will have a stronger impact for VRU protection. In contrast to smartphones used for retrofit in vehicles, smartphones used by VRUs are not connected to an external power supply. Furthermore, cyclists and pedestrians are more likely to be concerned about their personal safety than car drivers and may be less willing to allow the application to access their location data. This value has been developed together with 5GAA member input.

Figure 17 shows the penetration rates for smartphone C-ITS communication technical solutions assumed for the VRU protection case. The individual plots for each solution, also showing the intermediary steps, are presented in Annex A - Assumptions, Figure 29.

Figure 17: Modelled penetration rates for LTE-PC5, 802.11p and Cellular, among VRUs for the high penetration and the low penetration scenario for the VRU



3.2.2.3 Alert delivery rates

The modelling of alert delivery rates and network coverage and availability was the same for the VRU protection case as for the red signal violation case (see Section 3.2.1.3). However, different assumption was made on vehicle speed for the alert to be received by the relevant person (i.e. the vehicle driver) in sufficient time to allow action to be taken to avoid a potential collision were assumed[14].

3.2.2.4 Fraction of fatalities that can be mitigated

The proportions of fatalities which cannot be addressed or mitigated by the C-ITS technologies are the same as presented in the signal violation case (see Section 3.2.1.4).

3.2.2.5 Effectiveness of a received alert/warning message in appropriately affecting the behaviour of the driver

The effectiveness of warning messages on driver behaviour is assumed to be the same as presented in the signal violation case (see Section 3.2.1.5).

[14] A speed range between 20km/h – 60km/h has been used to evaluate an average alert delivery rate in urban roads. This implies that the signal is received within 22 metres from a possible collision, if the speed is 20km/h or within 86 meters if the vehicle is proceeding at the highest speed. For rural roads a speed range between 50km/h (i.e. 63m) and 100km (i.e.184m) has been used. The same assumptions have been used both for LTE-PC5 and 802.11p.

4 Modelling limitations and main assumptions

As with any modelling exercise of this nature, there are some restrictions on the accuracy and completeness of the results. This section briefly outlines some of the limitations that should be acknowledged in this study:

- The approach to modelling the ability of a vehicle to avoid an accident, and the timing and range of an alert signal to enable this to happen, is based on the 3GPP model from the previous Ricardo study. That study was focussed on V2V communication, so the model is optimised for such a scenario. No development of the model has taken place to optimise it for the present scenarios. Sensitivity analysis presented in this study showed that this is not expected to have a substantial impact on the results.
- Whilst data for coverage and availability of 4G-LTE networks are available and can be projected to future years, it is not clear to what extent the introduction of 5G services will cause the coverage and availability (of cellular signals sufficient to support the C-ITS services described in this report) to diverge from the projections for 4G-LTE. Similarly, it is not clear to what extent existing 3G signals could support safety-critical C-ITS services. The possible contributions of 3G and 5G to these applications have not been included in the current study as no data could be found on coverage and availability for 3G and 5G. In this sense, the presented assumptions are conservative and could, in practice, improve due to being complemented with 3G/5G.
- While there are still doubts and uncertainties around retrofitting, for the purposes of modelling, it has been assumed that smartphones may be used in vehicles for C-ITS services, that they will be able to receive a good signal (e.g. for accurate vehicle location through GPS signals, potentially enhanced through on-board sensors such as accelerometers) and that means of providing alerts to the driver (such as screens integrated into the vehicle dashboard or using the smartphone screen itself) will be available. These assumptions have not been confirmed by smartphone manufacturers or vehicle manufacturers and concerns have been raised by 5GAA members that GNSS accuracy through smartphones might not be sufficient for safety applications.
- The modelling applies factors to the number of accidents avoided to separately account for impaired drivers (through the effects of drugs or alcohol) and cases where the driver may be slow to react to the alert, or does not react appropriately (see factor ‘E’ as described in Section 3.1). There are also likely to be accidents in which vehicles still pass a red signal (because the alert is received too late to stop), but do so at a reduced speed. In these cases, the accident would probably be less severe than if no alert had been transmitted. The effects of this type of factor on reducing the severity of accidents instead of preventing them entirely have not been included in the modelling.
- Limits have been applied to the take-up of C-ITS services on mobile phones in the VRU protection case to reflect potential concerns of users such as, those about data privacy and security (for example, broadcasting their location while on a poorly-lit and deserted street). Further research is recommended to validate or update these assumed limits.
- It is recognised that a potential limitation of the VRU protection use case is the uncertainty in tracking and predicting numerous VRU movements and prioritising of which ones drivers should be informed about. There is a risk of false alarm levels being overly high or drivers being overloaded with information in areas with high pedestrian or cyclist density, which risks that drivers will become complacent to the warning alerts. This issue is based on the design of the service itself and has not been reflected in the modelling. However, we recommend that this could be investigated further in future research to assess the effectiveness of the messages to the drivers for different designs of the VRU protection service.
- Due to the lack of data on serious injuries, the numbers were extrapolated from the number of fatalities (12 serious injuries for each fatality [3]). While this gives a rough estimation of the magnitude of saved serious injuries, we acknowledge that C-ITS services might impact the number of fatalities and serious injuries differently.

5 Summary of findings

5.1 Results for Red Signal Violation

5.1.1 Red Signal Violation – Without retrofitting

For the first set of results presented here, only the equipment of new vehicles through built-in systems are considered in the C-ITS communication solution uptake in vehicles. The second set of results considers retrofitting of existing vehicles through smartphones.

The results for the red signal violation use case are presented as annual fatalities and serious injuries in Figure 18, the full results tables can be found in Annex C – Results, Table 19 and Table 20. Key results are:

- Due to the low penetration of C-ITS communication-enabled infrastructure for all three technical solutions, the impacts on safety in the initial years are low in all cases.
- In later years, the impacts for the LTE-Uu case are slightly higher than for LTE-PC5. This is mainly due to a more rapid penetration of cellular connectivity in new vehicles, which reaches 100% by 2022 compared to a full penetration for LTE-PC5 in 2025.
- 802.11p has lower road safety benefits, due to slower in-vehicle penetration and less favourable alert delivery rates.
- One limitation for LTE-Uu (cellular) solution is a lack of connected traffic signal infrastructure. A better penetration of traffic lights with communication functionality for the LTE-Uu (cellular) case, would have significant impacts on the results; however, industry experts have highlighted that it is unlikely that traffic lights will be connected quicker than RSU roll-out for LTE-PC5 or 802.11p.

Statistics on serious injuries from road traffic accidents are not publicly available but it is estimated that for every death on Europe's roads there are 12 serious injuries (4 permanently disabling injuries such as damage to the brain or spinal cord and 8 serious injuries) [3]. This assumption is, therefore, used to estimate the total number of serious injuries which could be saved; this has been added to the calculated fatalities saved to derive the results presented in Figure 18. Additional charts showing the impacts on just fatalities are presented in Annex D – Result charts presenting fatalities only.

Figure 18: Red signal violation - Total annual <u>fatalities and serious injuries</u> in the high scenario for the three C-ITS communication solutions in comparison to the baseline.

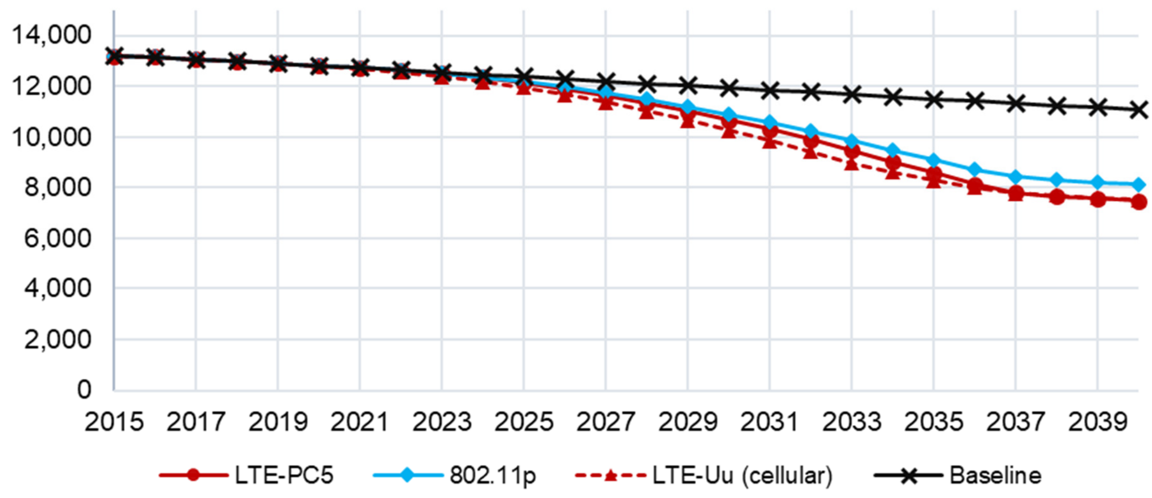
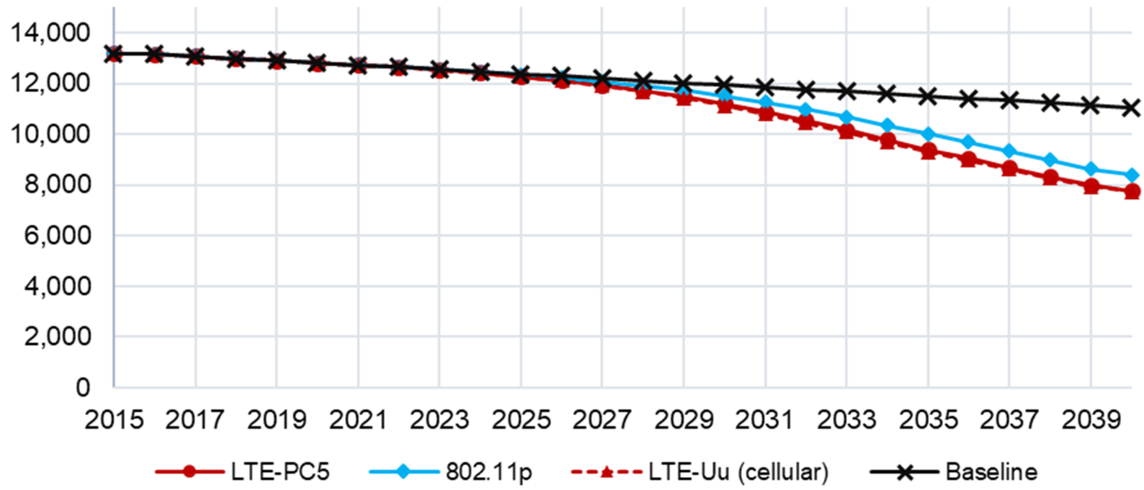


Figure 19 shows the same results discussed above for the low case scenario. In this scenario the impact of LTE-Uu and LTE-PC5 are almost equivalent.

Figure 19: Red signal violation - Total annual <u>fatalities and serious injuries</u> in low scenario for the three C-ITS communication solutions in comparison to the baseline.



5.1.2 Red Signal Violation – With retrofitting

The impact of retrofitting devices to vehicles is represented in Figure 20 and Figure 21 (for fatalities only), results tables can be found in Annex C – Results, Table 19 and Table 20. As expected, the impact of retrofitted devices is higher in the early stages because the penetration in into the existing fleet is not limited to new vehicles only. As soon as the penetration in the fleet increases, the impact of retrofitted devices is less important. As the results show, significant additional fatalities can be saved through considering retrofitting. Due to the limitations around integration of 802.11p (high/low scenario) and LTE-PC5 (low scenario) in smartphones the retrofitting impacts are zero and thus not presented below.

Figure 20: Red Signal Violation - Impacts of retrofitting for LTE-PC5 in the high scenario – Annual avoided fatalities

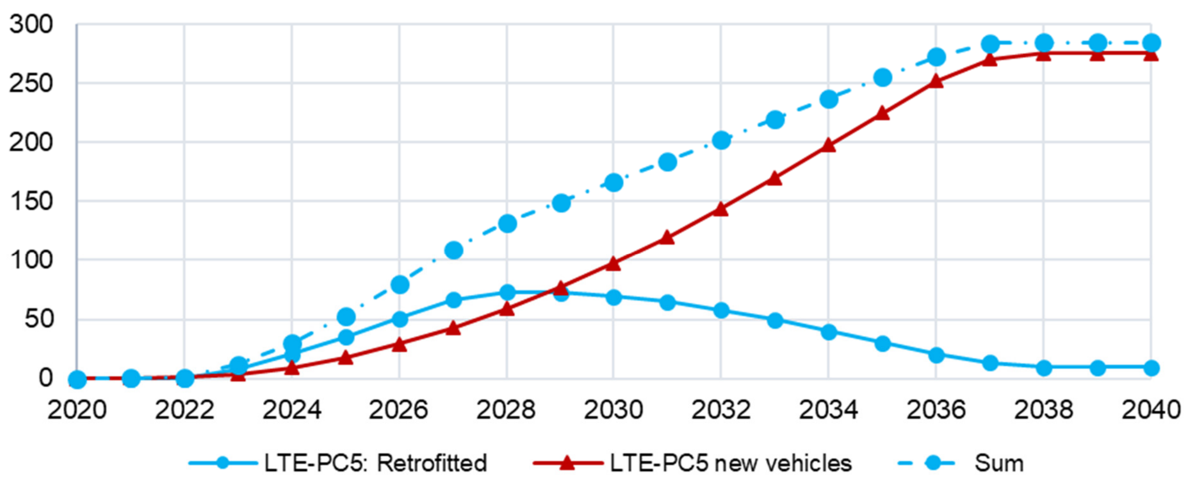
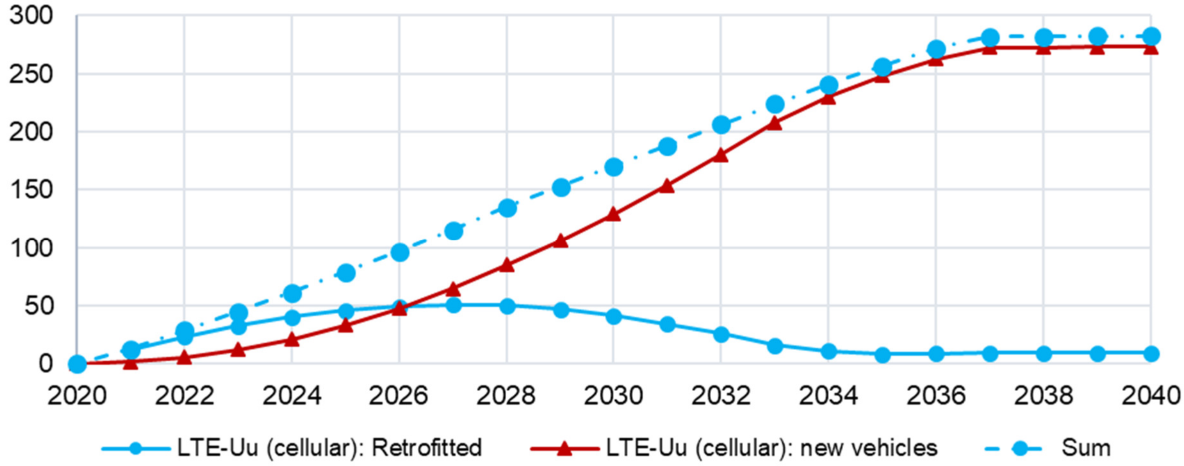


Figure 21: Red Signal Violation - Impacts of retrofitting for LTE-Uu (cellular) in the high scenario - Annual avoided fatalities



5.2 Results for Vulnerable Road User protection

5.2.1 Vulnerable Road User protection – Without retrofitting

For the first set of results presented here, only the equipment of new vehicles through built-in systems are considered in the C-ITS communication solution uptake in vehicles. The second set of results considers retrofitting of existing vehicles through smartphones.

The results (as shown in Figure 22 and Figure 23) highlight the following:

- Compared to the red signal violation use case the advantages of LTE-Uu over the other two technical solutions is higher in the VRU use case, due to the advantages in smartphone penetration in the high scenario.
- Since for 802.11p is not assumed to be implemented in smartphones, the impacts for that technical solution are zero in both the high and the low scenario.
- In the low scenario, no penetration is assumed in smartphones LTE-PC5, therefore the only technical solution which shows a positive impact in life savings is LTE-Uu (cellular).

In line with the assumptions presented above for the red signal violation use case, the number of serious injuries has been extrapolated from the number of fatalities using a factor of 12. Additional charts showing the impacts on just fatalities are presented in Annex D – Result charts presenting fatalities only.

Figure 22: VRU protection - Total annual <u>fatalities and serious</u> injuries in the high scenario for the two C-ITS communication solutions in comparison to the baseline.

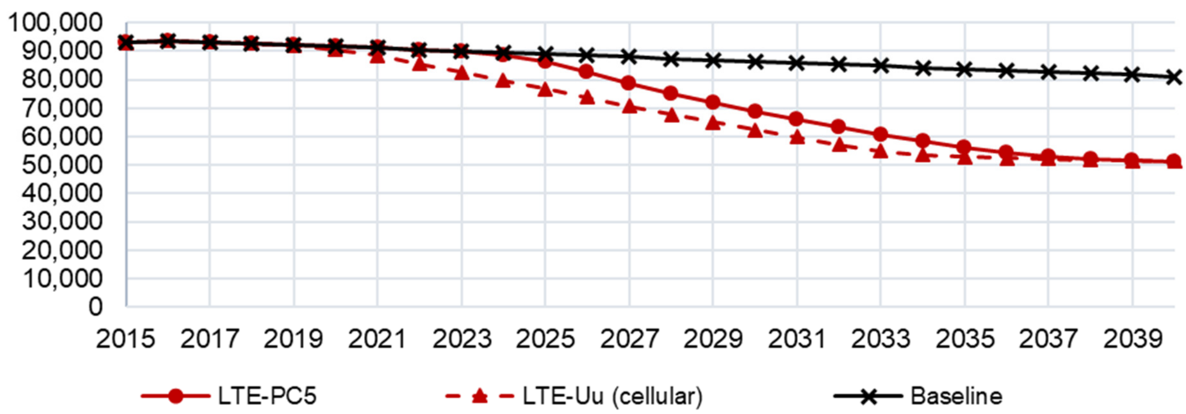
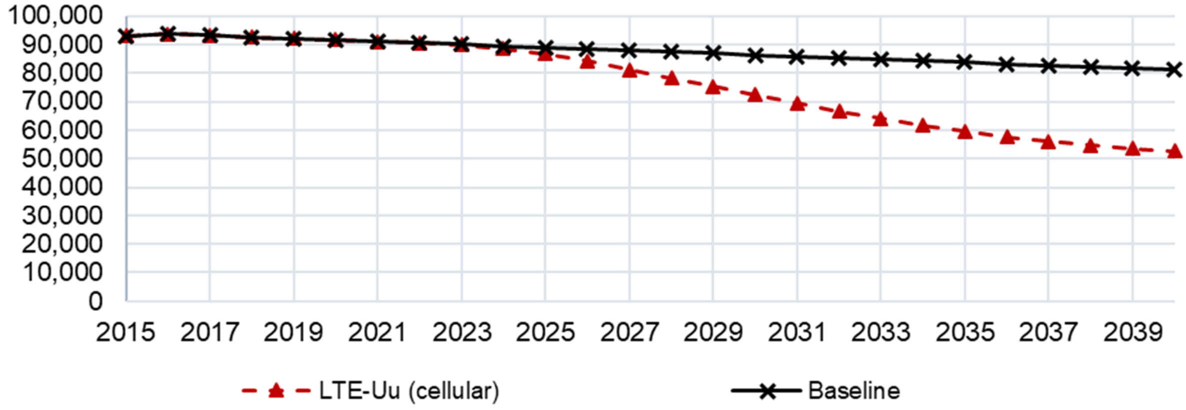


Figure 23: VRU protection - Total annual fatalities and serious injuries in the low scenario for the two C-ITS communication solutions in comparison to the baseline.



5.2.2 Vulnerable Road User protection – With retrofitting

The impact of retrofitting devices in vehicles in the VRU protection case is represented in Figure 24 and Figure 25 (for fatalities only). The safety impacts for both LTE-Uu and LTE-PC5 increase in earlier years. In particular LTE-Uu has significant positive impacts early on because of its high penetration in smartphones.

Figure 24: VRU protection - Impacts of retrofitting for LTE-PC5 in the high scenario – Annual avoided fatalities

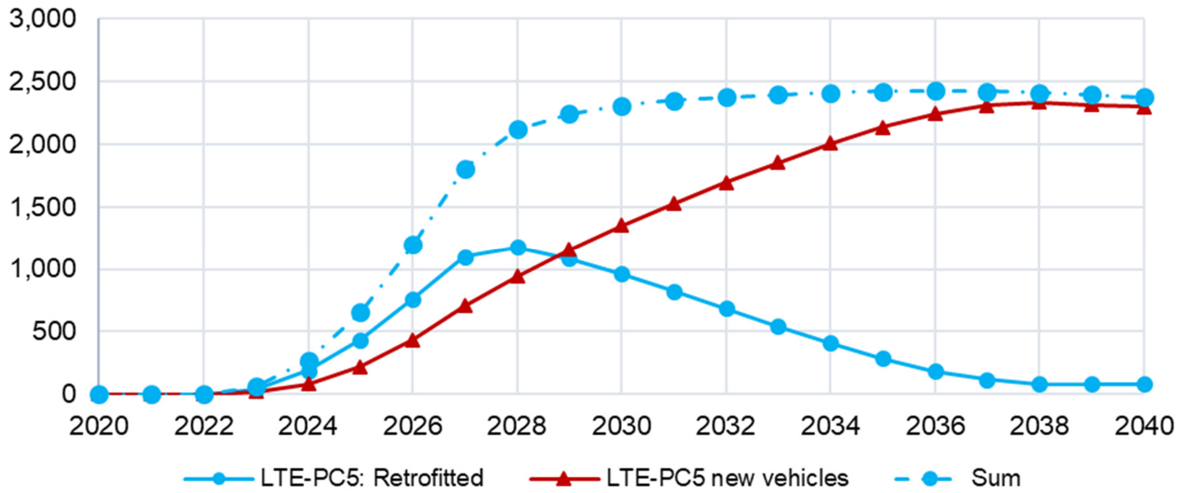
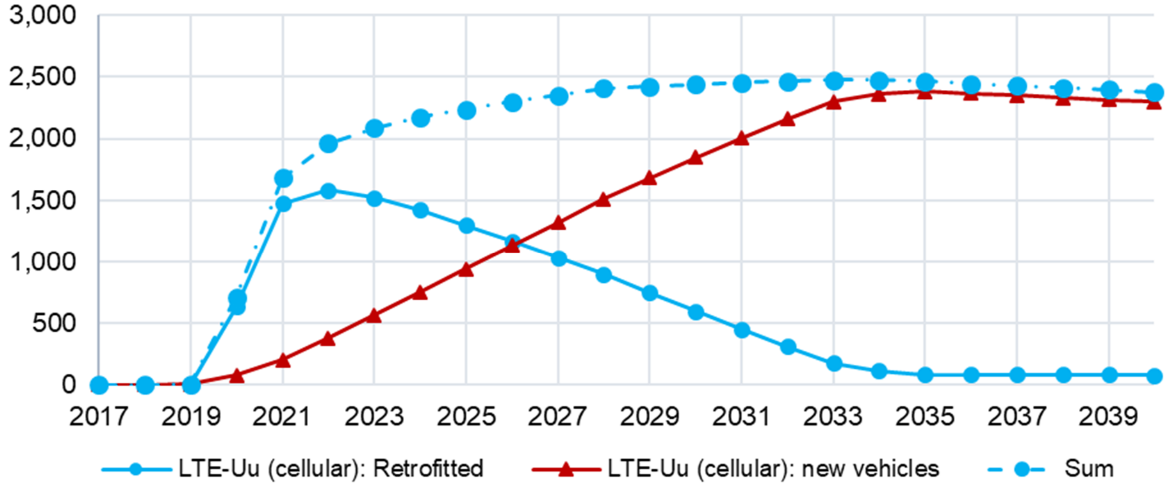


Figure 25: VRU protection - Impacts of retrofitting for LTE-Uu in the high scenario – Annual avoided fatalities



5.3 Aggregated results for both use cases

In this section results are presented on the cumulative avoided fatalities and serious injuries, aggregated for both use cases. Please note that there is some overlap between both use cases, where VRUs are involved in accidents due to red signal violations. This leads to a double-counting of a small amount of avoided accidents. The model as it stands does not allow separating out these accidents, however, as this would be a share of the red signal violation accidents which only amount to 12% of the total accidents assessed (in 2016, see Table 3 in Annex A – Assumptions) the overlap will be most likely below 10%. Thus, we have aggregated the results as a straight sum.

The aggregated results for both use cases (Figure 26) show that in the high scenario LTE-Uu shows the highest benefits in terms of the number of avoided fatalities and serious injuries. By 2040 the number of fatalities and serious injuries avoided through the use of the LTE-Uu solution reaches 114,066, compared to 90,380 for LTE-PC5. For the 802.11p solution the values are significantly lower at 27,144 as VRU protection is not supported through smartphones.

In the low scenario (see Figure 27), the direct communication solutions (LTE-PC5 and 802.11p) lie closer together in terms of cumulative avoided fatalities and serious injuries (24,241 and 17,400 in 2040 respectively), due to the assumption of zero uptake of these technologies in smartphones. LTE-Uu performance on the other hand is not facing the same technical barriers and shows significantly higher results with a cumulative number of 52,663 avoided fatalities and serious injuries in 2040.

Figure 26: Aggregated results for both use cases in the high scenario- Cumulative avoided fatalities and serious injuries - Without retrofitting

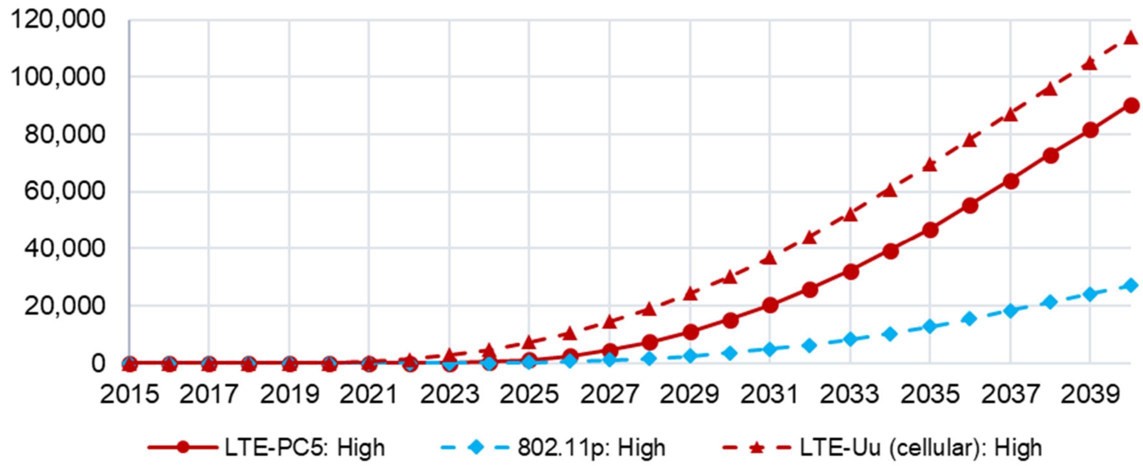
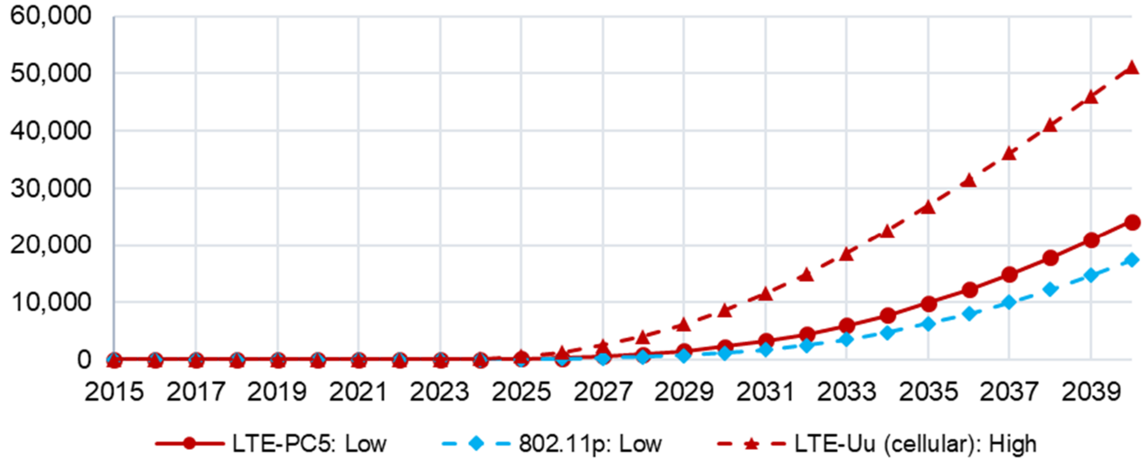


Figure 27: Aggregated results for both use cases in the low scenario- Cumulative avoided <u>fatalities and serious injuries</u> - Without retrofitting



6 Complementarity of LTE-Uu and LTE-PC5

While the modelling undertaken in this study assesses the impacts of LTE-PC5 and LTE-Uu separately, these two technical solutions should be thought of as integrated communication modes of the C-V2X ecosystem based on 3GPP technology. While LTE-PC5 is a direct communication mode operating in ITS band independently of the cellular network, LTE-Uu operates in the traditional mobile broadband spectrum [5].

5GAA experts believe that LTE-Uu, although showing superior benefits in this study, will eventually be combined with other sources of information such as on-board sensors and PC5 for the two use cases to be truly successful. Indeed, implementing the Use Cases based on a single technology may be prone to high number of false positives which may defeat their wide user adoption. In other words, in a safety-critical situation, there is a need to gather a large amount of redundant real-time information to make sure the vehicle can take the right decision.

One of the benefits of the 3GPP-based standards is that radio technologies are integrated to provide a seamless service. Because C-V2X requires minimum additional hardware to be introduced (over and above the LTE Rel-14 chipset) in order to facilitate C-ITS functionality, such as the Red Signal Violation and VRU protection use cases described in this study, its take-up is likely to quickly reach a large user base. Because LTE chipsets are likely to come with LTE-PC5, service penetration will depend on user adoption rather than on technology availability. The penetration base of LTE-PC5 could then be used to gain further benefits of a direct communication solution, as shown in the previous study [2].

7 Conclusions

The analysis presented in this report shows potential benefits from the application of C-ITS services to both, the red signal violation and VRU protection use cases. The overall number of fatalities saved is significantly greater in the VRU protection case, primarily because the baseline has a higher number of fatalities than the red signal violation case.

The current study is focussed on the use of vehicle-to-infrastructure and vehicle-to-pedestrian/cyclist communications for safety benefits. It should be noted that this complements a previous 5GAA study focussed on vehicle-to-vehicle communications [2].

In both use cases LTE-Uu (cellular) and LTE-PC5 C-ITS communications deliver greater benefits than 802.11p, as there is a higher uptake of the services through smartphones and embedded in-vehicle cellular communications. Due to insufficient data being available the analysis presented in this report is based on 4G-LTE cellular communications. As a result, this may be under-estimating the benefits of the roll-out of LTE-Uu (cellular) communication solution because it does not consider potential benefits of 3G and 5G networks supplementing 4G. Moreover, it is important to note that it is likely that LTE-PC5 and LTE-Uu will be deployed together in vehicles and smartphones. The two radios may show complementary benefits e.g. PC5 in areas with low network coverage or Uu in congested areas. The impact of this combined deployment has not been analysed in this report.

While we have modelled LTE-PC5 and LTE-Uu separately, in practice, the two technical solutions use very similar chip technology and device hardware and so may ultimately converge into a single technical solution.

The benefits of C-ITS (under all three communication solutions) for the red signal violation case are limited in the early years of deployment due to the need to roll-out connected infrastructure and the associated management systems (whether through roadside units for 802.11p or LTE-PC5, or connection to the cellular network for LTE-Uu). The benefits from 802.11p are also reduced because of the lower technology performance for this technical solution as well as the slower roll-out, as identified in previous 5GAA work [32]. A high penetration rate scenario shows slightly greater benefits across all technical solutions in early and mid-years (e.g. 2025 to 2035) due to the more rapid take-up of the services, with very similar results to the low penetration scenario by 2040.

The VRU protection use case shows greater benefits in early years as the take-up of the service is not dependent on the roll-out of roadside units and is largely available through the use of smartphone applications. Due to technical barriers for 802.11p roll-out in smartphones identified during this study, corresponding solutions based on 802.11p were found to be infeasible and consequently, only LTE-PC5 and LTE-Uu solutions were considered in the analysis.

Considering retrofitting of existing vehicles through smartphones significantly improves the impacts LTE-PC5 and LTE-Uu solutions. Due to the mentioned barriers for 802.11p roll-out in smartphones, this analysis does not consider 802.11p for retrofitting.

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A Assumptions

This annex contains a list of tables and graphs with the assumptions used in the model.

Table 3: Fatalities baseline for both use cases

	Baseline			Baseline	
Year	VRU fatalities	Number of fatalities due to RSV	Year	VRU fatalities	Number of fatalities due to RSV
2006	11954	1670	2023	6927	965
2007	12077	1647	2024	6887	959
2008	11698	1483	2025	6847	952
2009	10468	1326	2026	6806	945
2010	8988	1167	2027	6766	939
2011	8741	1197	2028	6726	932
2012	7965	1097	2029	6686	925
2013	7346	1028	2030	6646	918
2014	7290	1034	2031	6605	912
2015	7159	1015	2032	6565	905
2016	7208	1012	2033	6525	898
2017	7168	1006	2034	6485	892
2018	7128	999	2035	6445	885
2019	7088	992	2036	6405	878
2020	7047	985	2037	6364	871
2021	7007	979	2038	6324	865
2022	6967	972	2039	6284	858

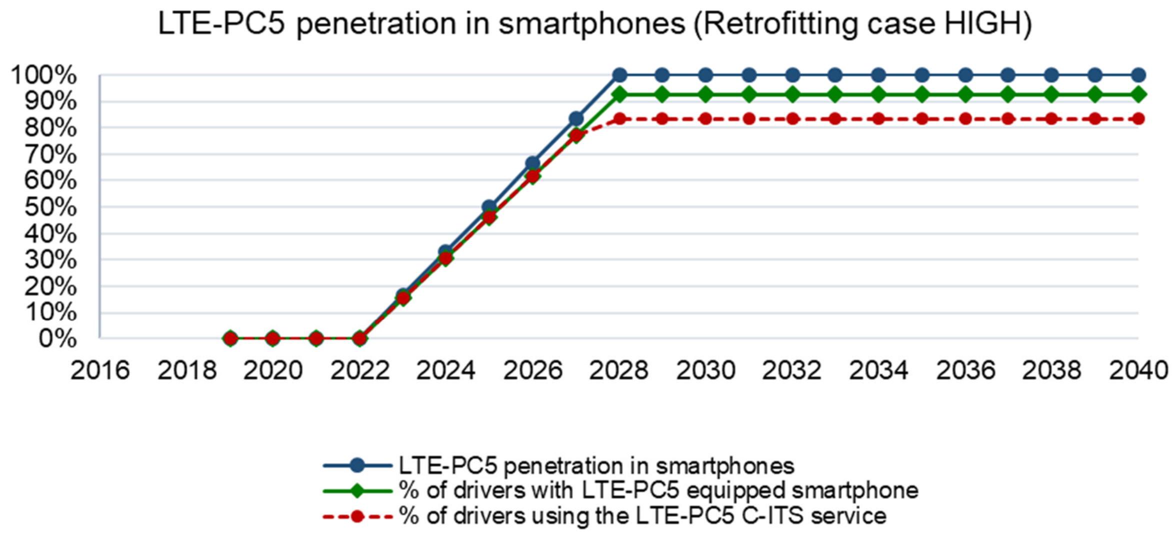
Table 4: C-ITS communication solution penetration in new vehicles

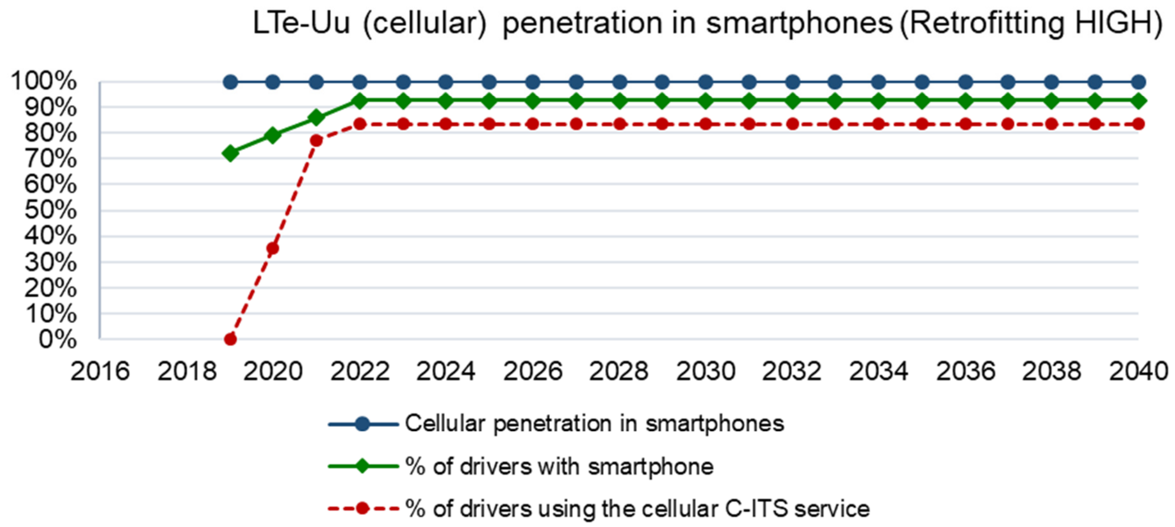
Year	Penetration in new vehicles LTE-PC5 Low	LTE-PC5 High	802.11p Low	802.11p High	LTE-Uu High	LTE-Uu Low
2006	0%	0%	0%	0%	0%	0%
2007	0%	0%	0%	0%	0%	0%
2008	0%	0%	0%	0%	0%	0%
2009	0%	0%	0%	0%	0%	0%
2010	0%	0%	0%	0%	0%	0%
2011	0%	0%	0%	0%	0%	0%
2012	0%	0%	0%	0%	0%	0%
2013	0%	0%	0%	0%	0%	0%
2014	0%	0%	0%	0%	0%	0%
2015	0%	0%	0%	0%	0%	0%
2016	0%	0%	0%	0%	0%	0%
2017	0%	0%	0%	0%	0%	0%
2018	0%	0%	0%	0%	0%	0%
2019	0%	0%	0%	0%	5%	5%
2020	4%	4%	5%	4%	55%	9%
2021	14%	14%	7%	14%	78%	19%
2022	25%	25%	9%	25%	100%	30%
2023	36%	50%	13%	50%	100%	41%
2024	50%	75%	21%	75%	100%	55%
2025	56%	100%	30%	100%	100%	61%
2026	63%	100%	38%	100%	100%	68%
2027	69%	100%	46%	100%	100%	74%
2028	75%	100%	55%	100%	100%	80%
2029	82%	100%	67%	100%	100%	87%
2030	88%	100%	81%	100%	100%	93%
2031	94%	100%	95%	100%	100%	99%
2032	100%	100%	100%	100%	100%	100%
2033	100%	100%	100%	100%	100%	100%
2034	100%	100%	100%	100%	100%	100%
2035	100%	100%	100%	100%	100%	100%
2036	100%	100%	100%	100%	100%	100%
2037	100%	100%	100%	100%	100%	100%
2038	100%	100%	100%	100%	100%	100%
2039	100%	100%	100%	100%	100%	100%
2040	100%	100%	100%	100%	100%	100%

Table 5: C-ITS communication solution penetration in smartphones (Retrofitting)

	Retrofitting penetration					
Year	LTE-PC5 Low	LTE-PC5 High	802.11p Low	802.11p High	LTE-Uu Low	LTE-Uu High
2006	0%	0%	0%	0%	0%	0%
2007	0%	0%	0%	0%	0%	0%
2008	0%	0%	0%	0%	0%	0%
2009	0%	0%	0%	0%	0%	0%
2010	0%	0%	0%	0%	0%	0%
2011	0%	0%	0%	0%	0%	0%
2012	0%	0%	0%	0%	0%	0%
2013	0%	0%	0%	0%	0%	0%
2014	0%	0%	0%	0%	0%	0%
2015	0%	0%	0%	0%	0%	0%
2016	0%	0%	0%	0%	0%	0%
2017	0%	0%	0%	0%	0%	0%
2018	0%	0%	0%	0%	0%	0%
2019	0%	0%	0%	0%	0%	0%
2020	0%	0%	0%	0%	0%	36%
2021	0%	0%	0%	0%	0%	77%
2022	0%	0%	0%	0%	0%	83%
2023	0%	15%	0%	0%	15%	83%
2024	0%	31%	0%	0%	31%	83%
2025	0%	46%	0%	0%	46%	83%
2026	0%	62%	0%	0%	62%	83%
2027	0%	77%	0%	0%	77%	83%
2028	0%	83%	0%	0%	83%	83%
2029	0%	83%	0%	0%	83%	83%
2030	0%	83%	0%	0%	83%	83%
2031	0%	83%	0%	0%	83%	83%
2032	0%	83%	0%	0%	83%	83%
2033	0%	83%	0%	0%	83%	83%
2034	0%	83%	0%	0%	83%	83%
2035	0%	83%	0%	0%	83%	83%
2036	0%	83%	0%	0%	83%	83%
2037	0%	83%	0%	0%	83%	83%
2038	0%	83%	0%	0%	83%	83%
2039	0%	83%	0%	0%	83%	83%
2040	0%	83%	0%	0%	83%	83%

Figure 28: Assumptions used to derive the penetration in smartphones for retrofitting case





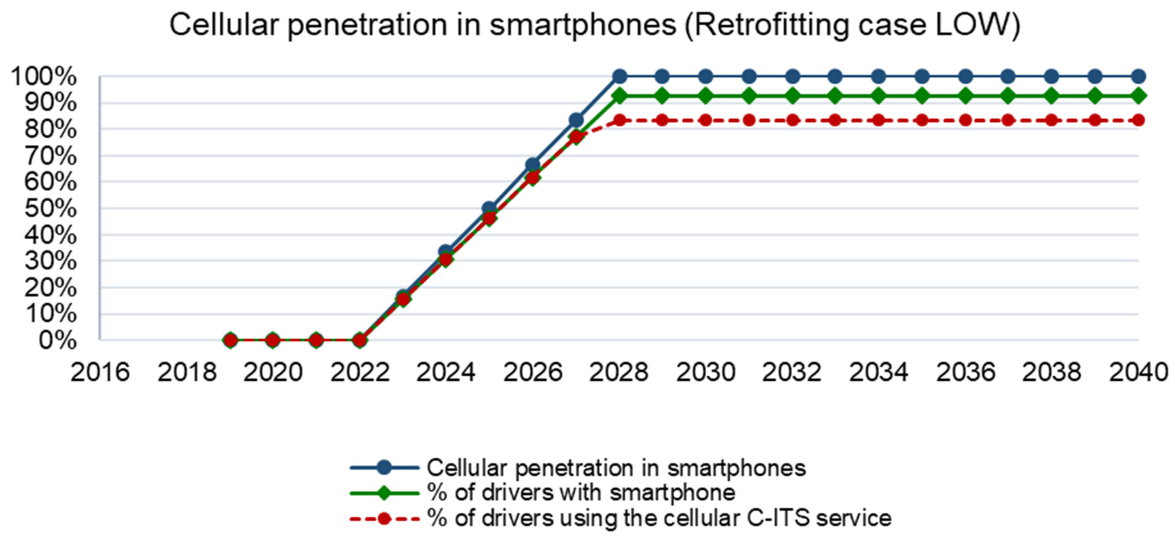


Table 6: Road side unit deployment in urban and rural scenarios

	Road side units			
	Urban High	Urban Low	Rural High	Rural Low
2016	0%	0%	0%	0%
2017	0%	0%	0%	0%
2018	0%	0%	0%	0%
2019	0%	0%	0%	0%
2020	0%	0%	0%	0%
2021	6%	0%	1%	0%
2022	12%	0%	3%	0%
2023	18%	6%	4%	1%
2024	24%	12%	5%	3%
2025	30%	18%	7%	4%
2026	36%	24%	8%	5%
2027	42%	30%	9%	7%
2028	48%	36%	10%	8%
2029	54%	42%	12%	9%
2030	60%	48%	13%	10%
2031	66%	54%	14%	12%
2032	72%	60%	16%	13%
2033	78%	66%	17%	14%
2034	84%	72%	18%	16%
2035	90%	78%	20%	17%
2036	96%	82%	21%	18%
2037	100%	88%	22%	19%
2038	100%	93%	24%	20%
2039	100%	99%	25%	21%
2040	100%	100%	26%	23%

Table 7: C-ITS communication solution penetration in smartphones (VRU case)

	Penetration in smartphones (VRU case)					
Year	LTE-PC5 Low	LTE-PC5 High	802.11p Low	802.11p High	LTE-Uu High	LTE-Uu Low
2006	0%	0%	0%	0%	0%	0%
2007	0%	0%	0%	0%	0%	0%
2008	0%	0%	0%	0%	0%	0%
2009	0%	0%	0%	0%	0%	0%
2010	0%	0%	0%	0%	0%	0%
2011	0%	0%	0%	0%	0%	0%
2012	0%	0%	0%	0%	0%	0%
2013	0%	0%	0%	0%	0%	0%
2014	0%	0%	0%	0%	0%	0%
2015	0%	0%	0%	0%	0%	0%
2016	0%	0%	0%	0%	0%	0%
2017	0%	0%	0%	0%	0%	0%
2018	0%	0%	0%	0%	0%	0%
2019	0%	0%	0%	0%	58%	0%
2020	0%	0%	0%	0%	63%	0%
2021	0%	0%	0%	0%	66%	0%
2022	0%	0%	0%	0%	66%	0%
2023	0%	14%	0%	0%	67%	14%
2024	0%	28%	0%	0%	67%	28%
2025	0%	42%	0%	0%	67%	42%
2026	0%	56%	0%	0%	67%	56%
2027	0%	67%	0%	0%	67%	67%
2028	0%	67%	0%	0%	67%	67%
2029	0%	67%	0%	0%	67%	67%
2030	0%	67%	0%	0%	67%	67%
2031	0%	67%	0%	0%	67%	67%
2032	0%	67%	0%	0%	67%	67%
2033	0%	67%	0%	0%	67%	67%
2034	0%	67%	0%	0%	67%	67%
2035	0%	67%	0%	0%	67%	67%
2036	0%	67%	0%	0%	67%	67%
2037	0%	67%	0%	0%	67%	67%
2038	0%	67%	0%	0%	67%	67%
2039	0%	67%	0%	0%	67%	67%
2040	0%	67%	0%	0%	67%	67%

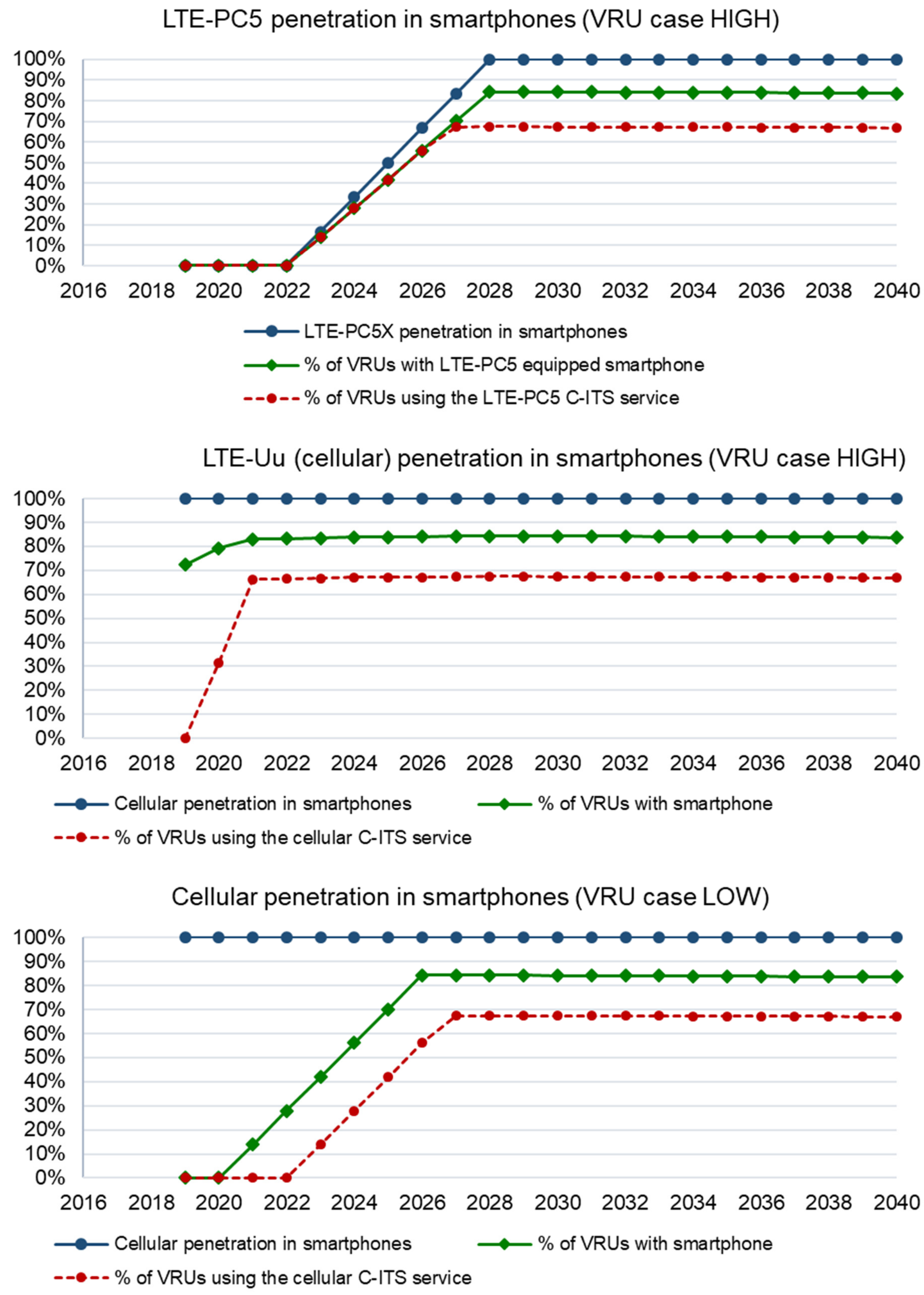
Table 8: 4G coverage and availability in urban scenario

	Coverage & Availability Urban			
	Coverage High	Availability High	Coverage Low	Availability Low
2016	96%	72%	96%	72%
2017	96%	74%	96%	74%
2018	97%	76%	96%	75%
2019	97%	78%	97%	77%
2020	97%	80%	97%	78%
2021	97%	82%	97%	80%
2022	98%	84%	97%	81%
2023	98%	85%	98%	83%
2024	98%	87%	98%	84%
2025	98%	89%	98%	86%
2026	98%	91%	98%	87%
2027	98%	93%	98%	89%
2028	98%	95%	98%	90%
2029	98%	95%	98%	92%
2030	98%	95%	98%	93%
2031	98%	95%	98%	95%
2032	98%	95%	98%	95%
2033	98%	95%	98%	95%
2034	98%	95%	98%	95%
2035	98%	95%	98%	95%
2036	98%	95%	98%	95%
2037	98%	95%	98%	95%
2038	98%	95%	98%	95%
2039	98%	95%	98%	95%
2040	98%	95%	98%	95%

Table 9: 4G coverage and availability in rural scenario

	Coverage & Availability Rural			
	Coverage High	Availability High	Coverage Low	Availability Low
2016	82%	84%	82%	84%
2017	84%	85%	83%	85%
2018	86%	87%	85%	86%
2019	88%	88%	86%	87%
2020	89%	90%	88%	88%
2021	91%	91%	89%	90%
2022	93%	92%	91%	91%
2023	95%	94%	92%	92%
2024	95%	95%	94%	93%
2025	95%	95%	95%	94%
2026	95%	95%	95%	95%
2027	95%	95%	95%	95%
2028	95%	95%	95%	95%
2029	95%	95%	95%	95%
2030	95%	95%	95%	95%
2031	95%	95%	95%	95%
2032	95%	95%	95%	95%
2033	95%	95%	95%	95%
2034	95%	95%	95%	95%
2035	95%	95%	95%	95%
2036	95%	95%	95%	95%
2037	95%	95%	95%	95%
2038	95%	95%	95%	95%
2039	95%	95%	95%	95%
2040	95%	95%	95%	95%

Figure 29: Assumptions used to derive the penetration in smartphones (VRU)



B Alert delivery reliability from 3GPP model

This annex presents the alert delivery reliability rates modelled with the 3GPP model [33].and used in the previous [2] and current study.

This annex covers **802.11p** and **LTE-PC5** and is divided into three main sections:

- B.1 - System-level evaluation methodology: In this section the methodology and assumptions used in the system-level simulations of LTE-PC5 and 802.11p are described. These apply to the computational model developed to quantify the delivery reliability rates for the two technologies in a number of evaluation scenarios; namely, the urban (grid model) and rural (2-lane linear model) scenarios. We have re-used the methodology adopted by 3GPP [32] to evaluate LTE-PC5 and 802.11p. The parameters and assumptions used in the modelling of the performance of 802.11p have been derived from studies performed by the NGMN [34]. We have also extended the evaluation methodology to cover rural scenarios, as well as vehicle-to-pedestrian communications for rural scenarios.
- B.2 - Performance evaluation results: In this section the results derived from the computational model are described. Curves showing the delivery reliability rates as a function of the stopping distance are given for different speeds and technologies for each of the scenarios described above.
- B.3 - Link between system-level evaluation scenarios and modelled accident scenarios: The final section describes how the results derived from the computational model have been used in quantifying the performance of LTE-PC5 and 802.11p for a number of accident scenarios.

B.1 System-level evaluation methodology

B.1.1 System level simulation assumptions

For PC5-based LTE-V2V and V2P, the following general assumptions apply:

- User equipment (UE) autonomous resource selection (a.k.a mode 4) is considered.
- Each vehicle UE's reception is subject to the half-duplex constraint; i.e., a vehicle UE cannot perform transmission and reception operations simultaneously within a transmission time interval of 1 millisecond.

B.1.2 Evaluation scenarios

Table 10 presents the parameters used in the evaluation of LTE-PC5.

Three cases for the *dropping* (specifying the locations) of vehicle UEs are defined: urban case and rural case. The UE drop and mobility model in each case is described in the next section together with a description of the drop model for pedestrian UEs.

Furthermore, for the evaluation of PC5-based LTE-V2P, the following conditions apply:

- Pedestrian UEs coexist in the same 10 MHz channel as all vehicle UEs.
- P2V (i.e., pedestrian UE transmission and vehicle UE reception) is considered to characterise PC5-based LTE-V2P performance.
- Separate statistics are considered for P2V and V2V.
- For the purpose of saving power, pedestrian UEs will not monitor all the subframes continuously in the way vehicle UEs do. Instead, pedestrian UEs use partial sensing and monitor only a subset of the subframes (20 out of 100 subframes are considered in the present study).

Table 11 shows additional parameters used in the evaluation of 802.11p.

Table 10: Parameters for the evaluation of LTE-PC5

<table>
<tr><th colspan="2">Parameter</th><th>Assumptions</th></tr>
<tr><td colspan="2">Carrier frequency</td><td>PC5-based LTE-V2V: 6 GHz</td></tr>
<tr><td colspan="2">Bandwidth</td><td>PC5-based LTE-V2X: 10 MHz</td></tr>
<tr><td colspan="2">Number of carriers</td><td>One 10 MHz carrier</td></tr>
<tr><td colspan="2">Frequency resource allocation</td><td>12 physical resource blocks for 190 bytes
16 physical resource blocks for 300 bytes</td></tr>
<tr><td colspan="2">Modulation</td><td>QPSK</td></tr>
<tr><td colspan="2">Synchronization</td><td>Frequency error (i.e., error in the oscillator)
in the range of ± 0.1 PPM.</td></tr>
<tr><td rowspan="7">Vehicle UE
Pedestrian UE</td><td>In-band emission</td><td>In-band emission model is reused with
{W, X, Y, Z} = {3, 6, 3, 3}
for single cluster SC-FDMA.</td></tr>
<tr><td>Antenna height</td><td>1.5 m for vehicle UE and pedestrian UE</td></tr>
<tr><td>Antenna pattern</td><td>Omni 2D</td></tr>
<tr><td>Antenna gain</td><td>3 dBi for vehicle UE and 0 dBi for pedestrian UE</td></tr>
<tr><td>Maximum transmit power</td><td>23 dBm</td></tr>
<tr><td>Number of antennas</td><td>1 TX and 2 RX antennas.
2 RX antennas are separated by wavelength/2.</td></tr>
<tr><td>Noise figure</td><td>9 dB</td></tr>
</table>

Table 11: Additional parameters for the evaluation of 802.11p.

Parameter	Assumptions
CCA/CS	-85 dBm
CCA/ED	-65 dBm
Modulation/bit rate	QPSK 0.5 code rate, 6 Mbps
Symbol interval (including GI)	8 us
Number of data sub-carriers	52
Sub-carrier spacing	156.25 kHz
PLCP preamble	32 us
PLCP signal	8 us
Slot time	13 us
EDCA	AC_VO
AIFSN	2

Parameter	Assumptions
CCA/CS	-85 dBm
CWmin	3
AIFS	58 us, AIFS = (AIFSN×Slot)+SIFS where SIFS = 32 us

B.1.3 UE drop and mobility model

Figure 30 and Figure 31 illustrate the road configurations for the urban and rural evaluation scenarios.

Vehicle UEs are dropped on the roads according to a spatial Poisson process. The vehicle density is determined by the assumed vehicle speed; i.e., average inter-vehicle distance in the same lane is set to 2.5 second multiplied by the absolute vehicle speed. Vehicle location is updated every 100 ms in the simulation.

In the urban evaluation scenario, the probability of a vehicle changing its direction at an intersection is as follows:

- Vehicle continues to go straight: probability of 0.5
- Vehicle turns left: probability of 0.25
- Vehicle turns right: probability of 0.25

Details of the drop and mobility models for the vehicle UEs and pedestrian UEs for each of urban and rural evaluation scenarios are shown below.

Figure 30: Road configuration for urban evaluation scenario

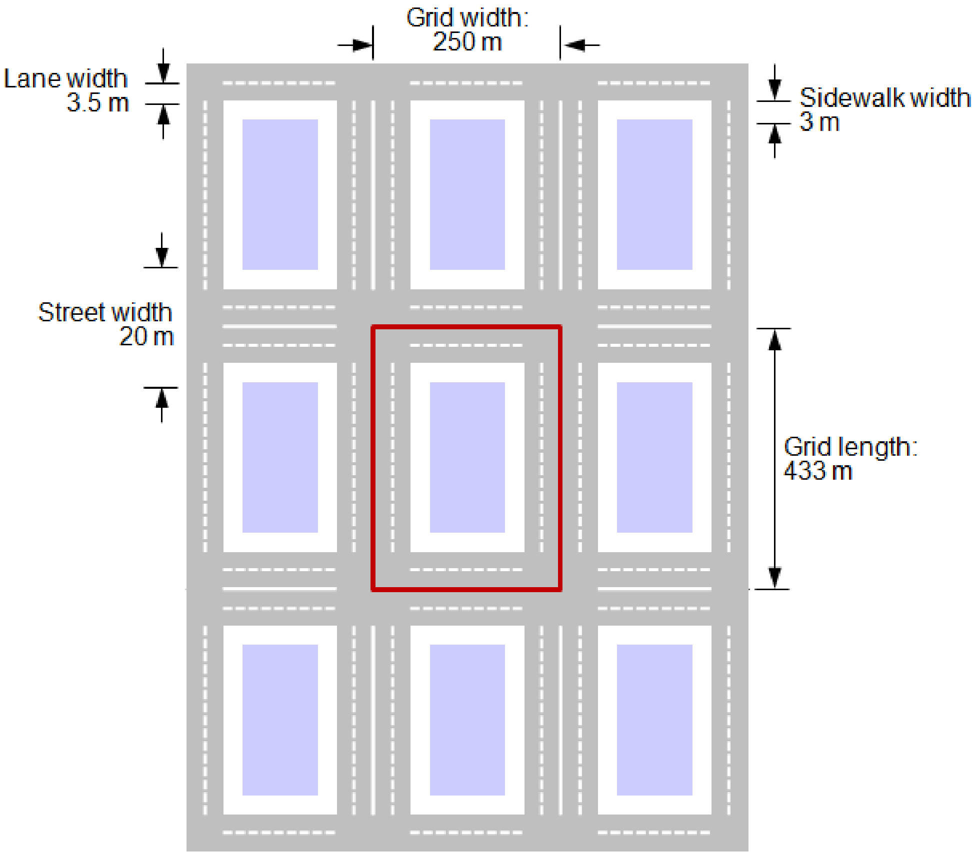


Figure 31: Road configuration for rural evaluation scenario

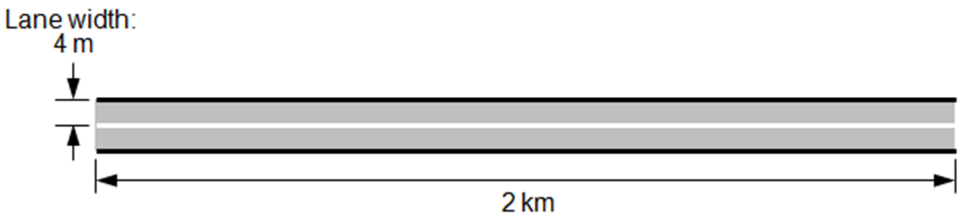


Table 12: Vehicle UE and pedestrian UE drop and mobility models.

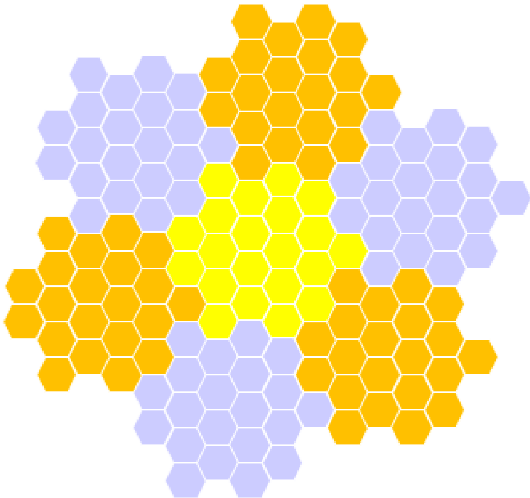
Parameter	Urban case	Rural case
Number of lanes	2 in each direction. 4 lanes in total in each street.	1 in each direction. 2 lanes in total in the rural roads.
Lane width	3.5 m	4 m
Road grid size by the distance between intersections	433 m × 250 m. Note that 3 m is reserved for sidewalk per direction (no vehicle or building in this reserved space).	N/A
Simulation area size	1732 m × 750 m with 14 road grids. Wrap around is applied to the simulation area according to the figure in this annex.	Freeway length = 2000 m. Wrap around is applied to the simulation area according to the figure in this annex.
Vehicle density	Average inter-vehicle distance in the same lane is 2.5 sec × absolute vehicle speed. The same density/speed is used in all the lanes in one simulation.	
Absolute vehicle speed	15, 30, 40, 50, 60, 70, 80 km/h.	60, 70, 80, 90, 100 km/h
Pedestrian UE location	Equally spaced in the middle of the sidewalk	Equally spaced along the edge of the rural roads
Total number of pedestrian UEs	500	20M (pedestrian clusters), where M is uniformly distributed between 2 and 3.
Inter-pedestrian UE distance	36.34 m[15]	0 m for intra pedestrian cluster and 200 m for inter pedestrian cluster
Absolute pedestrian speed	3 km/h	

[15] The value is obtained by dividing the total sidewalk length by the total number of pedestrians, i.e., [(250m – 17m) + (433m – 17m)] × 2 × 14 / 500 = 36.34 m.

B.1.4 Wrap around model

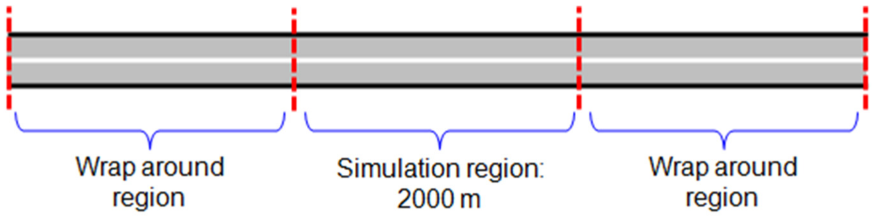
The wrap around model for the urban and rural evaluation scenarios are shown in Figure 32 and Figure 33.

Figure 32: Wrap around model for the urban evaluation scenario.



Note: The sides of the hexagons is 500/3 metres.

Figure 33: Wrap around model for the rural evaluation scenario.



B.1.5 Channel models

The radio propagation channels modelled between vehicle UEs are described in Table 13.

Table 13: Vehicle-to-vehicle channel model

Parameter	Urban case	Rural cases
Pathloss model	WINNER+ B1 Manhattan grid layout. Note that the antenna height should be set to 1.5 m. Pathloss at 3 m is used if the distance is less than 3 m.	LOS in WINNER+ B1. Note that the antenna height should be set to 1.5 m. Pathloss at 3 m is used if the distance is less than 3 m.
Shadowing distribution	Log-normal	Log-normal
Shadowing standard deviation	3 dB for LOS and 4 dB for NLOS	3 dB
Decorrelation distance	10 m	25 m
Fast fading	NLOS with fixed large scale parameters during the simulation.	

Vehicle-to-vehicle channels are updated during the simulation as follows:

- N is the number of vehicle UEs in system simulation.
- Initialization (at time 0).
- N vehicle locations are generated per implemented drop model.
- $PL(0)$: $N \times N$ matrix generated as per vehicle locations and implemented channel models.
- Shadowing (in log domain) $S(0)$: $N \times N$ i.i.d. normal matrix generated as per implemented shadowing model (with the condition that shadowing between two vehicles should be the same in the two directions).
- $Fading(0)$: $N \times N$ i.i.d. processes with a common distribution.
- Update (at time $100 \times n$ ms).
- Vehicle locations are updated as per implemented update rules.
- $PL(n)$: $N \times N$ matrix generated as per updated vehicle locations.
- $S(n) = \exp(-D/D_{corr})S(n-1) + \sqrt{\{1-\exp(-2D/D_{corr})\}}\, N_{S(n)}$
- where $N_{S(n)}$ is an $N \times N$ i.i.d. normal matrix generated as per the implemented shadowing model (with the condition that shadowing between two vehicles should be the same in the two directions),
- D is the update distance matrix where $D(i,j)$ is change in distance of link i to j from time $n-1$ to time n.
- Fading process is not impacted due to vehicle location updates – fading is only updated due to time.
- UE performance should reflect fast fading variation within the subframe.

For the channel model between a pedestrian UE and a vehicle UE, we reuse the vehicle-to-vehicle path loss, fading, and shadowing models with the following modifications:

- Pedestrian UE speed is 3 km/h.
- Location update is not modelled for pedestrian UE.
- Antenna height and gain of pedestrian UE are 1.5 m and 0 dBi, respectively

B.1.5.1 Traffic model for V2V

Table 14 shows the parameters used for the generation of periodic V2V communications traffic.

Table 14: Message generation period for V2V periodic traffic

Vehicle drop scenarios	Absolute vehicle speed (km/h)	Message generation period (ms)	Message size (bytes)
Urban	15 – 80	100	One 300-byte message followed by four 190-byte messages
Rural	50 – 100	100	

Note: The time instance of 300-byte size message generation is randomized among vehicles. Different message sizes are not distinguished in calculating the performance metric. The calculated packet reception ratio is the value averaged over the five messages.

B.1.5.2 Traffic model for V2P

The traffic model for P2V communications (pedestrian UE transmission and vehicle UE reception) is based on a fixed message size of 300 Bytes, and a fixed message generation period of 1000 ms.

B.1.6 Performance metric

The packet reception ratio (PRR) is considered for the evaluation of the performance of direct communications between road users. For one transmitted packet, the PRR is calculated as X/Y, where Y is the number of road users that are located in the range $N(a,b)$ from the transmitter, and X is the number of road users with successful reception among Y.

Average PRR is calculated as $(X1 + X2 + X3 \ldots + Xn)/(Y1 + Y2 + Y3 \ldots + Yn)$ where n denotes the number of generated messages in the simulation, with $a = 20i$ metres, $b = 20(i + 1)$ metres for i = 0, 1, 25.

B.2 Performance evaluation results

The various system-level simulation assumptions and parameters for LTE- PC5 and 802.11p are presented in the previous section. Note that *packet reception ratio* is used as the performance metric, and indicates the packet reception reliability for a road user to correctly receive messages within a given range (circled area), or in other words, the level of environmental awareness of its vicinity enabled by the underlying radio technology.

The system-level simulation results for both LTE-PC5 and 802.11p for urban and rural evaluation scenarios are presented in Figure 34 to Figure 41 below. Observe that LTE-PC5 outperforms 802.11p in packet reception ratio for all road type scenarios, and for all vehicle speeds (15 to 80 km/h for urban and 60 to 100 km/h for rural), which can be attributed to both link-level and system-level gains.

At the link level, LTE-PC5 is endowed with higher transmit power spectral density (thanks to frequency-domain multiplexing transmission), more power-efficient SC-FDM waveform, better (Turbo) channel coding gain, and physical layer packet re-transmissions. At the system level, LTE-PC5 better manages resources – it allows vehicles to learn other vehicles' resource usage patterns and to either select those resources that are clean and unoccupied or to reuse resources occupied by vehicle(s) that are sufficiently separated geographically.

Figure 34: LTE-V2V PRR performance in urban grid scenario

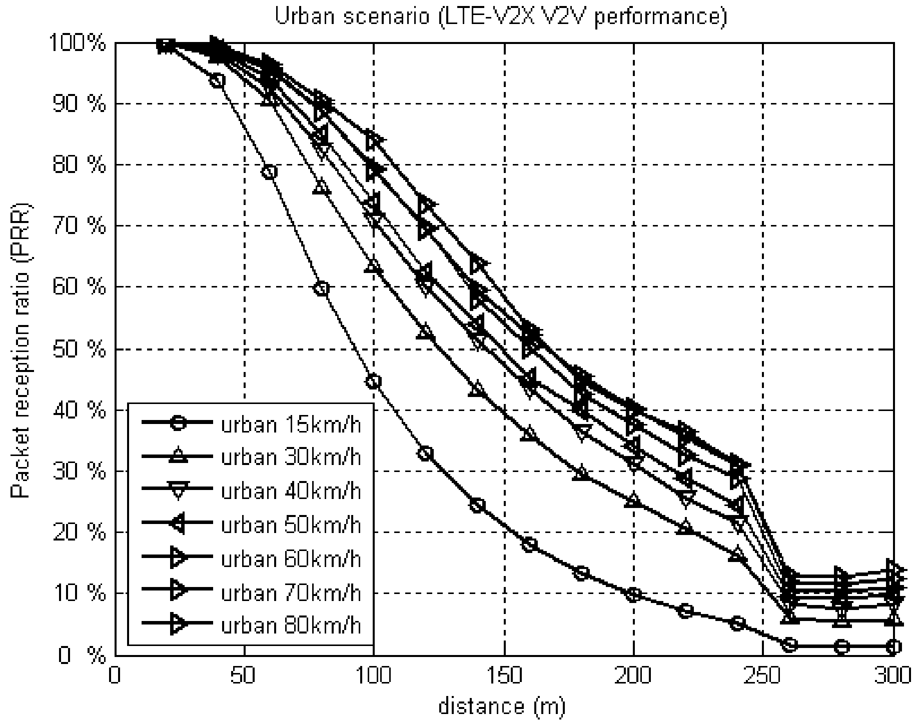


Figure 35: 802.11p V2V PRR performance in urban grid scenario

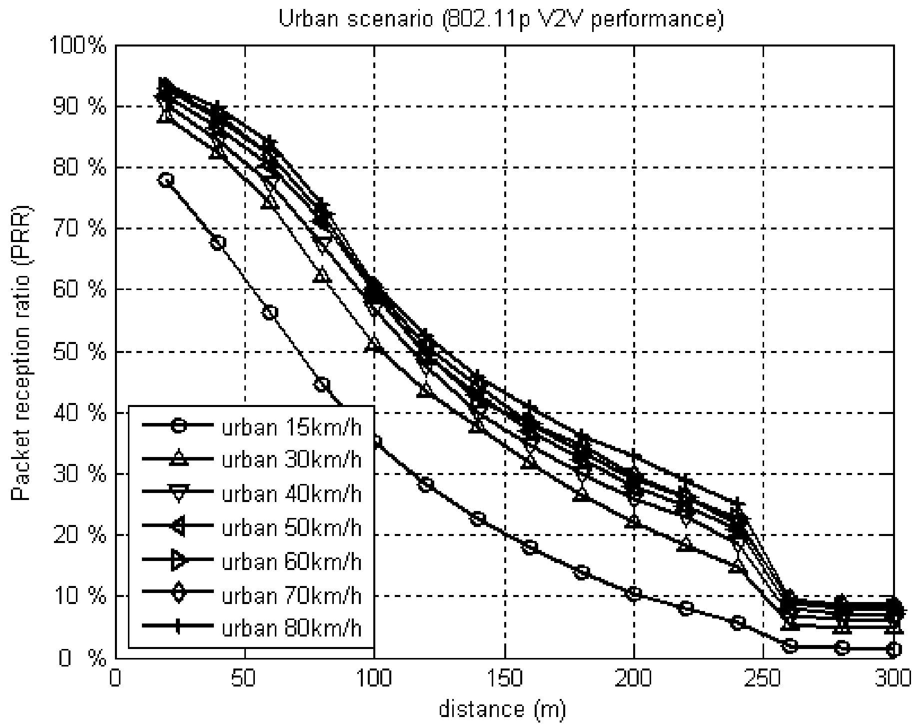


Figure 36: LTE-V2P PRR performance in urban grid scenario

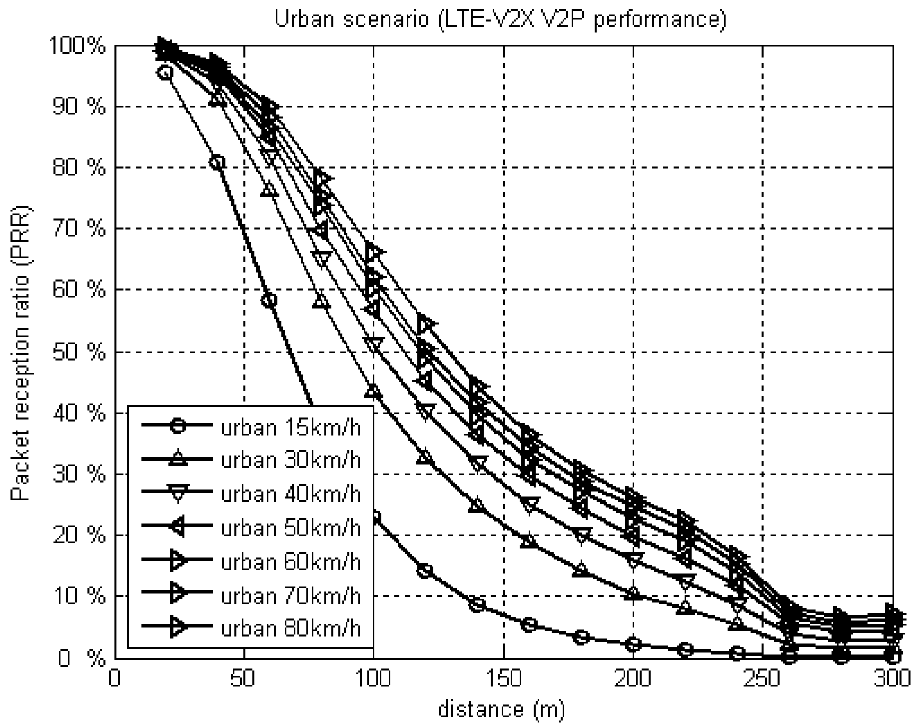


Figure 37: 802.11p V2P PRR performance in urban grid scenario

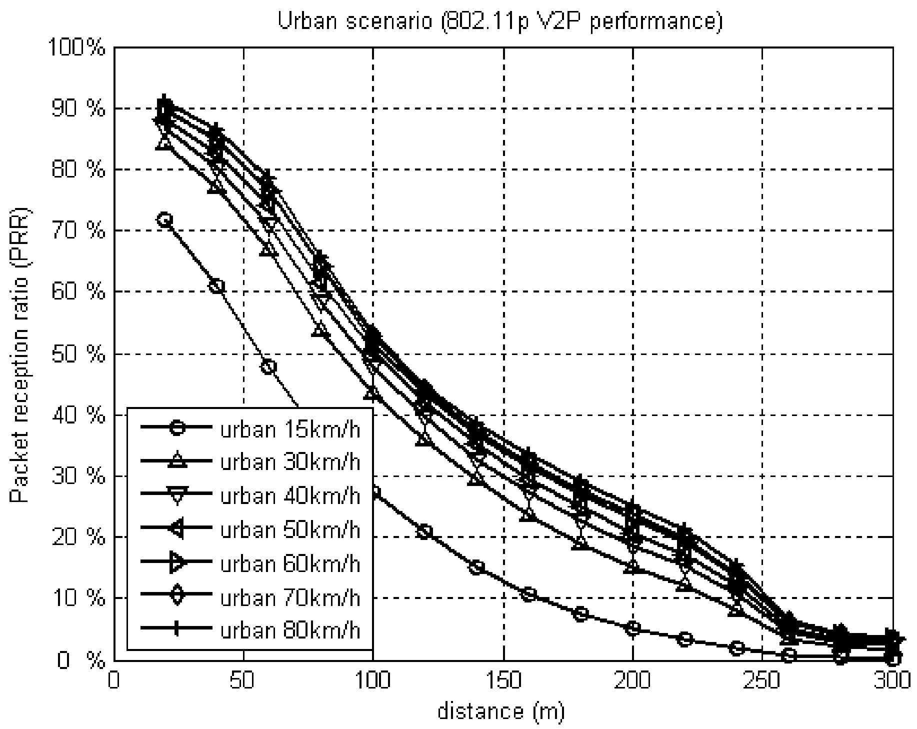


Figure 38: LTE-V2V PRR performance in 2-lane rural scenario.

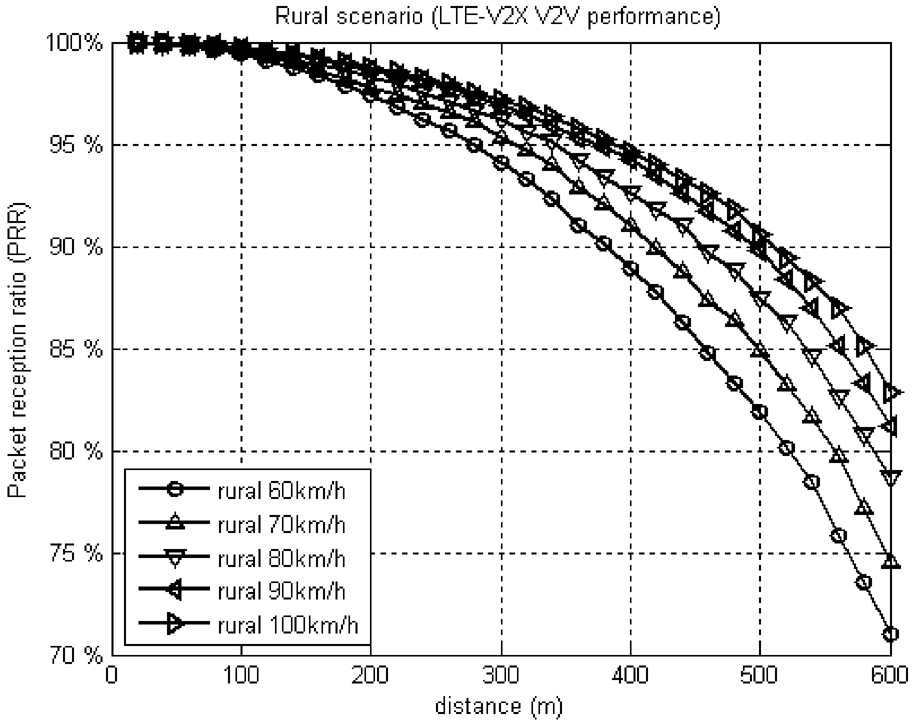


Figure 39: 802.11p V2V PRR performance in 2-lane rural scenario

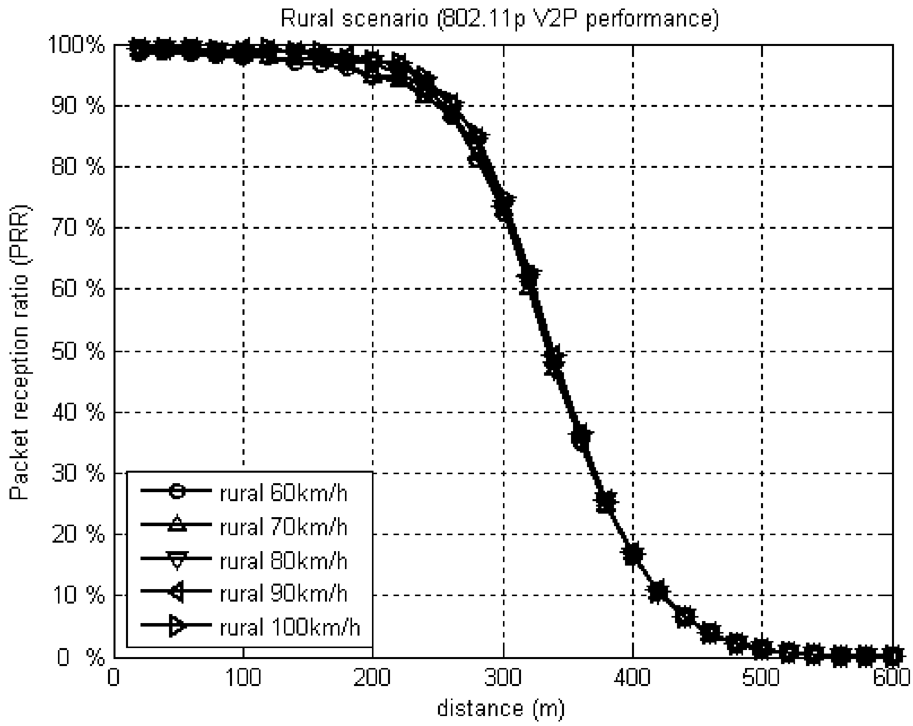


Figure 40: LTE-V2P PRR performance in 2-lane rural scenario

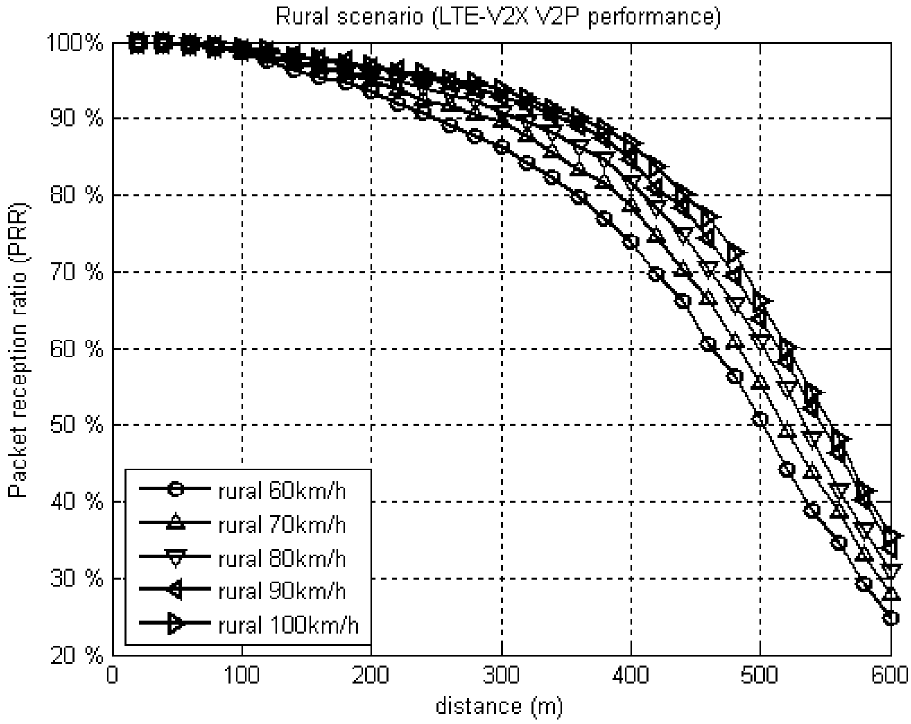
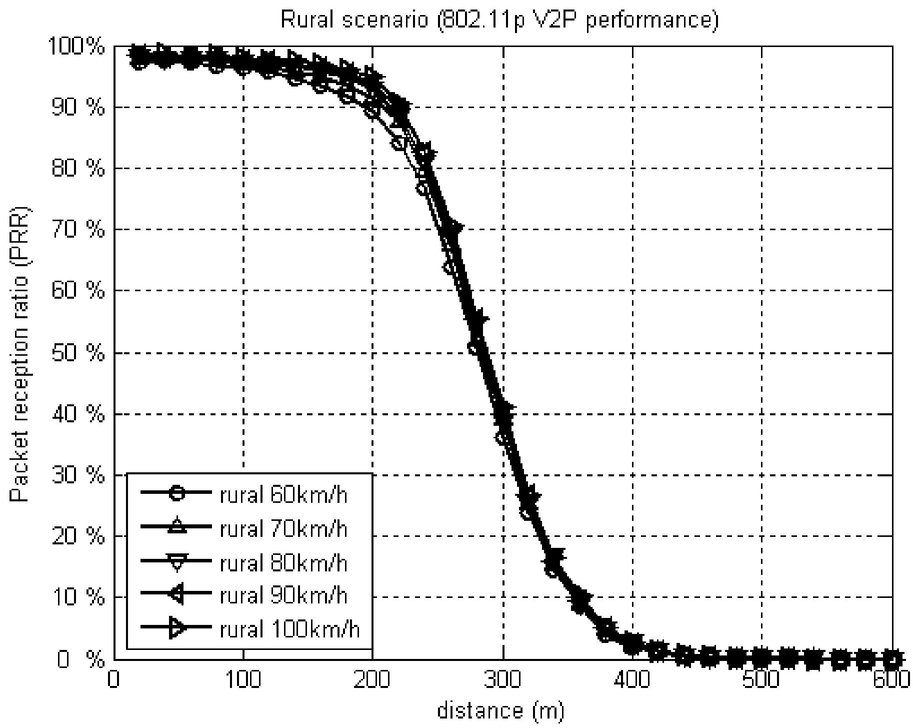


Figure 41: 802.11p V2P PRR performance in 2-lane rural scenario



B.3 Link between system-level evaluation scenarios and modelled accident scenarios

B.3.1 Link with modelled accident scenarios

The evaluation scenarios described above have been used to calculate the alert delivery reliability for LTE-PC5 and 802.11p. Table 15 provides a link between the evaluation scenarios and the accident scenarios modelled in this report. Note the speed range associated with each modelled scenario. These ranges will be used to calculate the alert delivery reliability rates for the described accident scenarios.

Table 15: Link between system evaluation scenarios and modelled accident scenarios

Road type	Type of accident	Mode of accident	Evaluation scenario	Speed km/h
Urban	Junction	Vehicle / vehicle Vehicle / motorbike	Grid/urban scenario V2V performance	15 - 40
	Junction	Vehicle / pedestrian Vehicle / cyclist	Grid/urban scenario V2 smartphone performance	15 - 40
	Not at junction	Vehicle / vehicle Vehicle / motorbike	Grid/urban scenario V2V performance	20 – 60
	Not at junction	Vehicle / pedestrian Vehicle / cyclist	Grid/urban scenario V2 smartphone performance	20 – 60
Rural	Junction	Vehicle / vehicle Vehicle / motorbike	Grid/urban scenario V2V performance	50 – 80
	Junction	Vehicle / pedestrian Vehicle / cyclist	Grid/urban scenario V2 smartphone performance	50 – 80
	Not at junction	Vehicle / vehicle Vehicle / motorbike	2-lane rural scenario V2V performance	50 – 100
	Not at junction	Vehicle / pedestrian Vehicle / cyclist	2-lane rural scenario V2 smartphone performance	50 – 100

B.3.2 AASHTO model, safe stopping distance and reliability at a specific speed

Using the outputs from the evaluation scenarios as plotted in Figure 34 to Figure 41, the alert delivery reliability rate for a number of speeds is derived. In order to extract the correct reliability rate for a specific speed, it is necessary to calculate the required safe stopping distance at that speed. The alert delivery reliability rate for a specific speed can then be read off the curve of reliability vs. distance for the said speed at the point where the distance is equal to the safe stopping distance.

The safe stopping distance can be calculated using the AASHTO model [35] and is given by

$$d = 0.278\ V\ t + 0.039\ V^2 / a,$$

where d is the required safe stopping distance in metres, V is the design speed in km/h, t the brake reaction time in seconds, and a the deceleration rate in m/s^2. The first linear term corresponds to the distance traversed during the brake reaction time. The second quadratic term corresponds to the stopping sight distance needed for the vehicle to decelerate to a complete stop. The recommended values for t and a are 2.5 seconds 3.4 m/s^2, respectively.

Based on the AASHTO model, the corresponding stopping sight distances for the considered speed range are summarized in the table below:

Table 16: Vehicle speed and stopping sight distance based on AASHTO model

Vehicle speed	Stopping sight distance
15 km/h	13.01 m
30 km/h	31.17 m
40 km/h	46.15 m
50 km/h	63.43 m
60 km/h	82.99 m
70 km/h	104.86 m
80 km/h	129.01 m
90 km/h	155.46 m
100 km/h	184.21 m
110 km/h	215.24 m
120 km/h	248.58 m
130 km/h	284.20 m
140 km/h	322.12 m

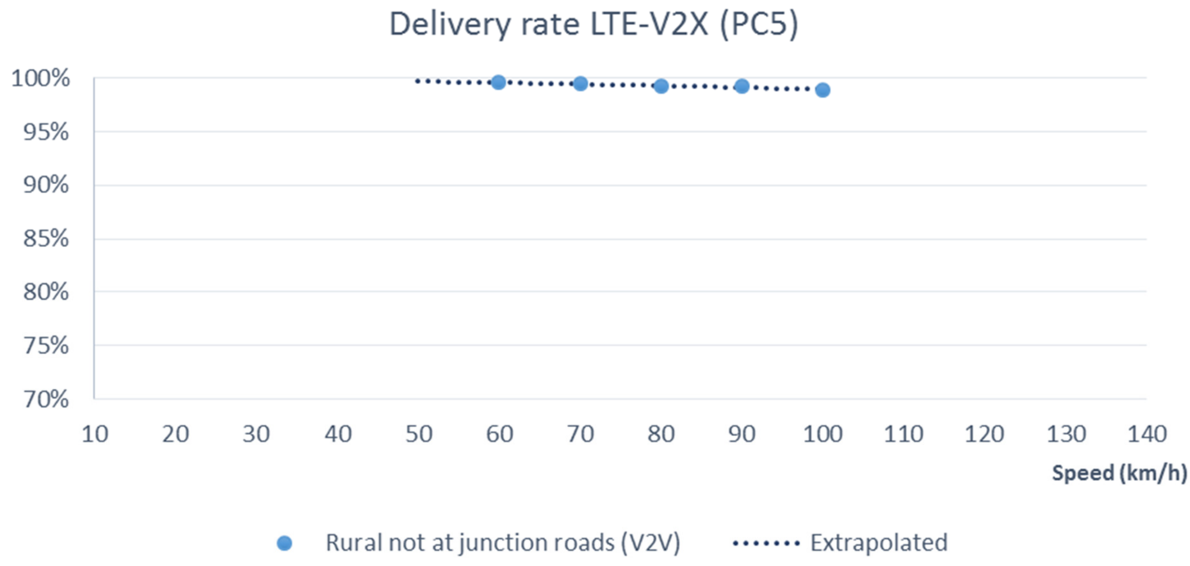
B.3.3 Derivation of alert delivery reliability for a given accident scenario

The above description explains how the reliability rate can be derived for a specific speed in a given accident environment. The overall reliability rate for the said environment can then be calculated by averaging the reliabilities over the range of speeds associated with the environment.

For example, consider the derivation of alert delivery reliability for LTE-V2V (PC5) in an urban junction environment. The first step is to locate the LTE-V2V (PC5) system-level performance curves for the urban environment. Next, for each simulated performance curve corresponding to a given vehicle speed (e.g., 60 km/h), record the packet reception ratio (i.e., 87.37%) at the corresponding stopping sight distance (82.99 m) by referring to the speed-distance mapping of the above table. Finally, the overall LTE-V2V (PC5) alert delivery reliability rate in an urban junction environment can be obtained by averaging the delivery rates over the range of associated speeds (i.e., 15-40 km/h).

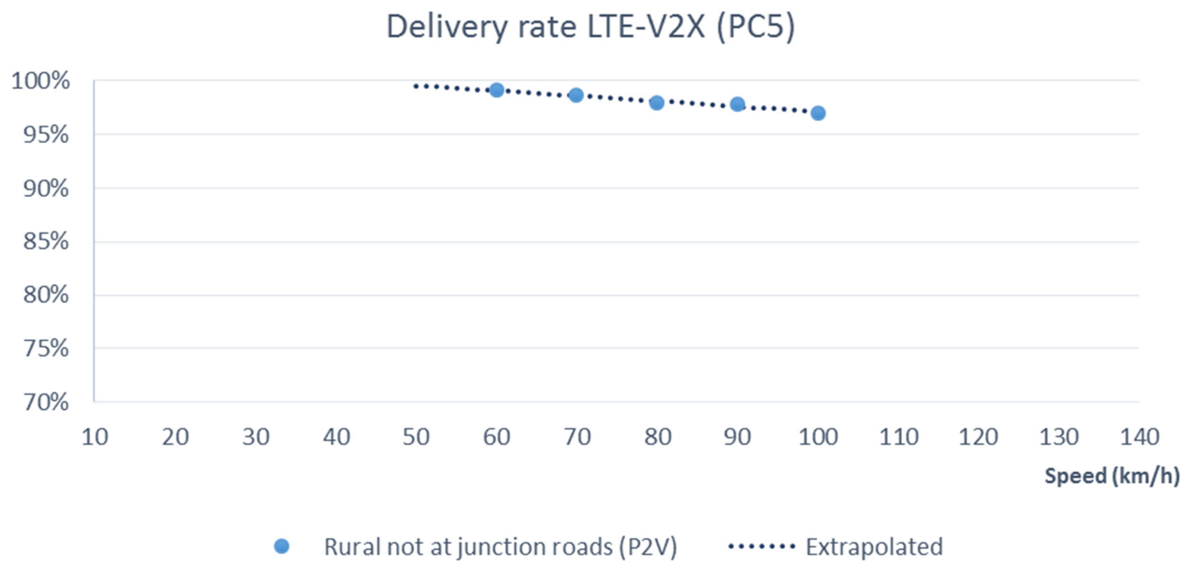
Figure 42 to Figure 49 below present extrapolated values of alert delivery reliability rates as a function of speed for LTE-PC5 and 802.11p in the accident environments of interest.

Figure 42: LTE-V2V (PC5) alert delivery reliability – not at junction model – rural



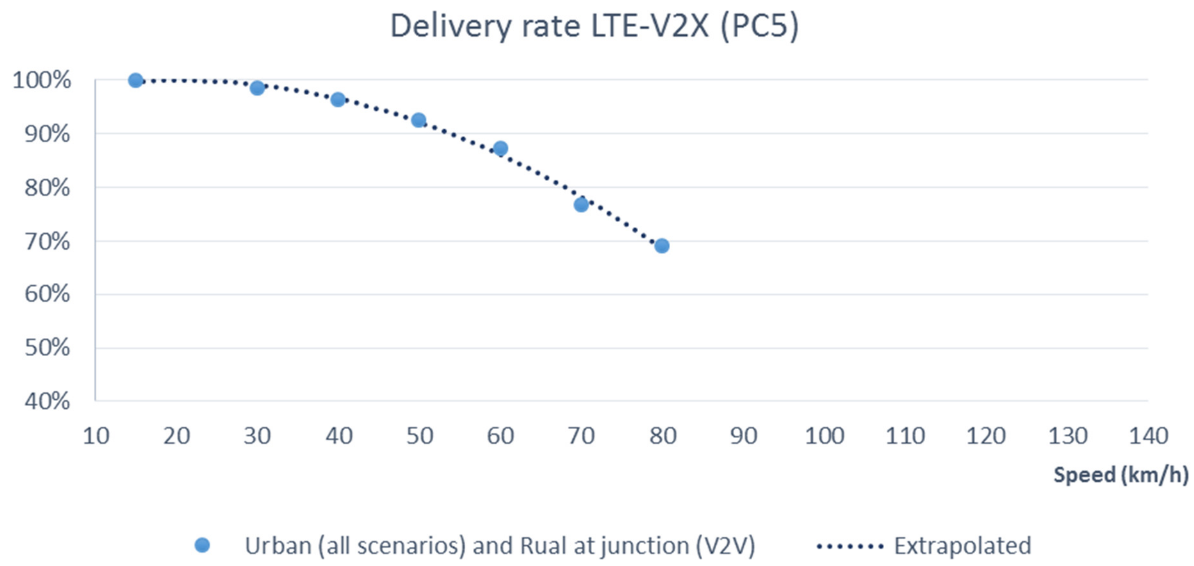
Note: Average over 50-100 km/h for rural V2V/V2M.

Figure 43: LTE-V2P alert delivery reliability – not at junction model – rural



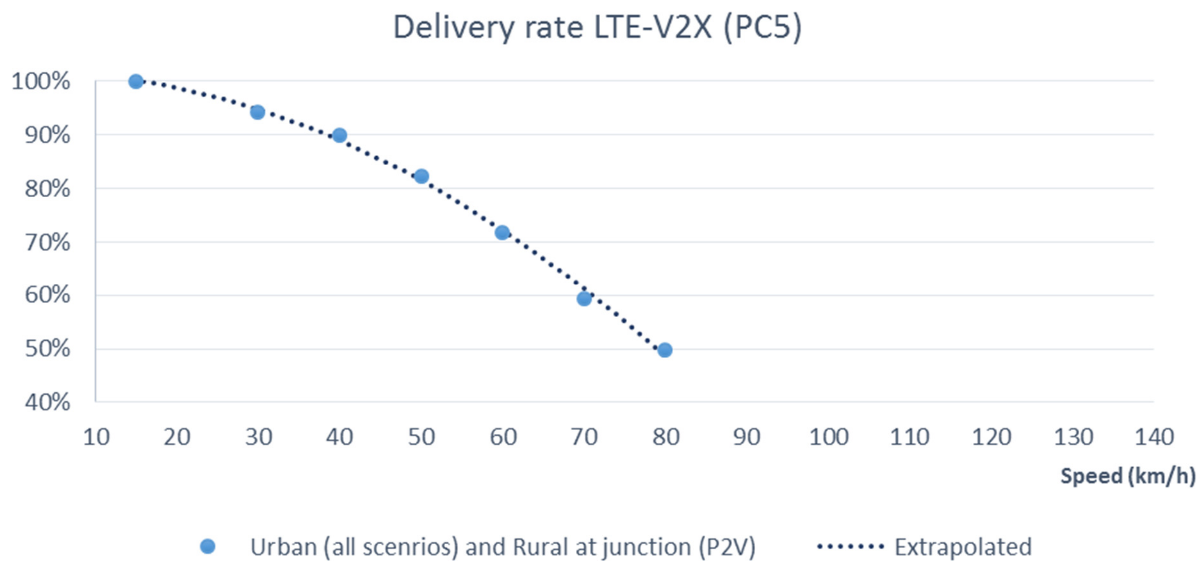
Note: Average over 50 to 100 km/h for rural V2P.

Figure 44: LTE-V2V (PC5) alert delivery reliability – junction model – urban



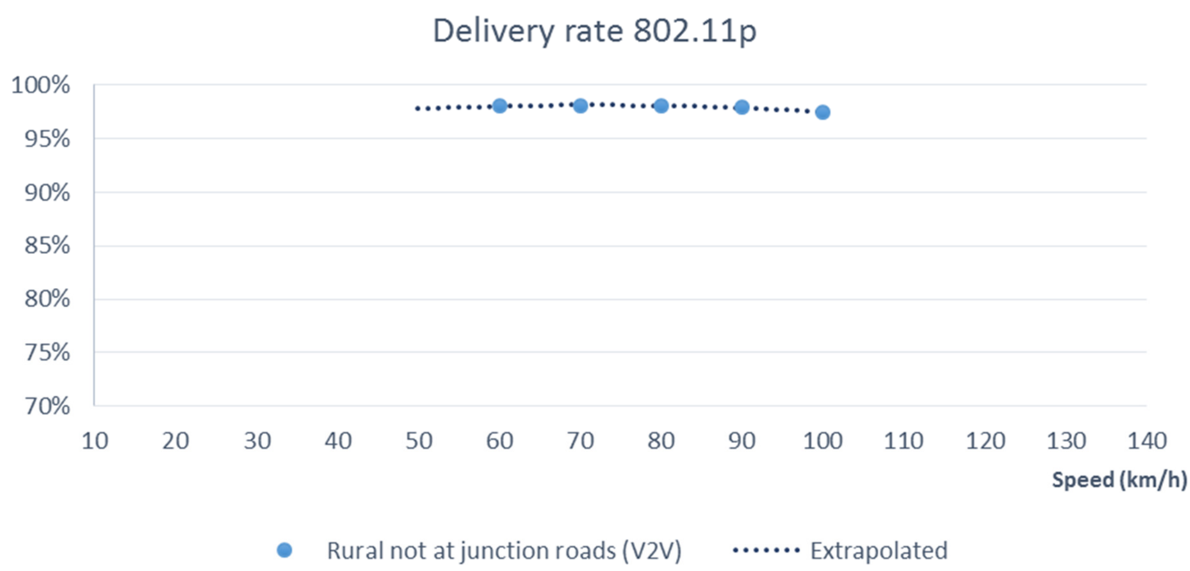
Note: Average over 15-40 km/h for urban at junction V2V/V2M. Average over 50-80 km/h for V2V/V2M rural at junction. Average over 20-60 km/h for urban not at junction V2V/V2M.

Figure 45: LTE-V2P (PC5) alert delivery reliability – Junction model – urban



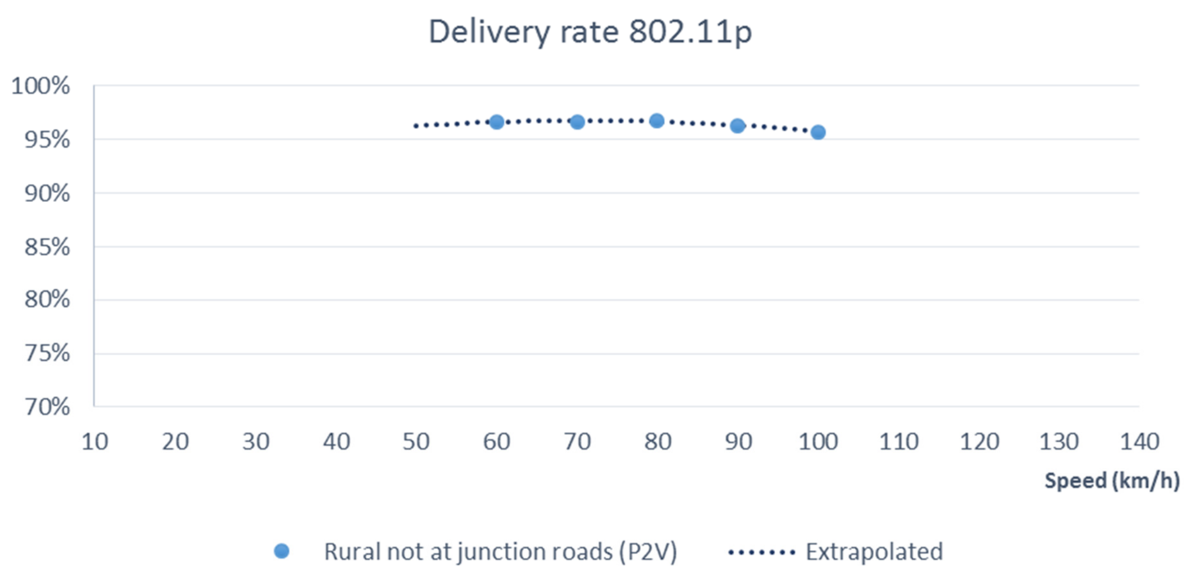
Note: Average over 15-40 km/h for urban V2P. Average over 50-80 km/h for V2P rural at junction. Average over 20-60 km/h for urban not at junction V2P.

Figure 46: 802.11p alert delivery reliability – not at junction model – rural V2V



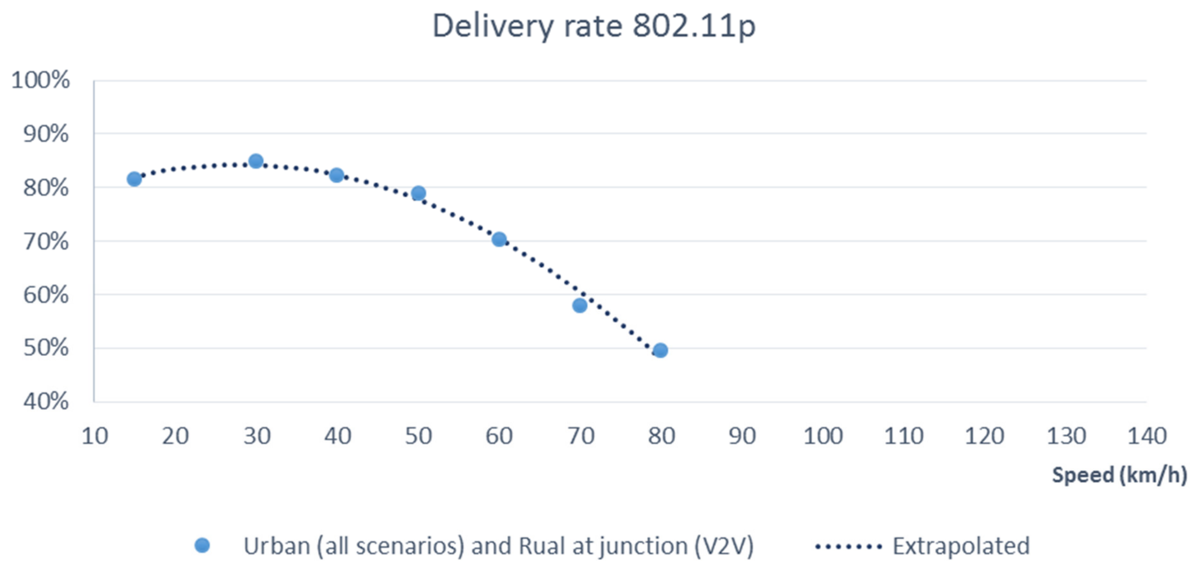
Note: Average over 50-100 km/h for rural V2V/V2M.

Figure 47: 802.11p alert delivery reliability – not at junction model – rural V2P



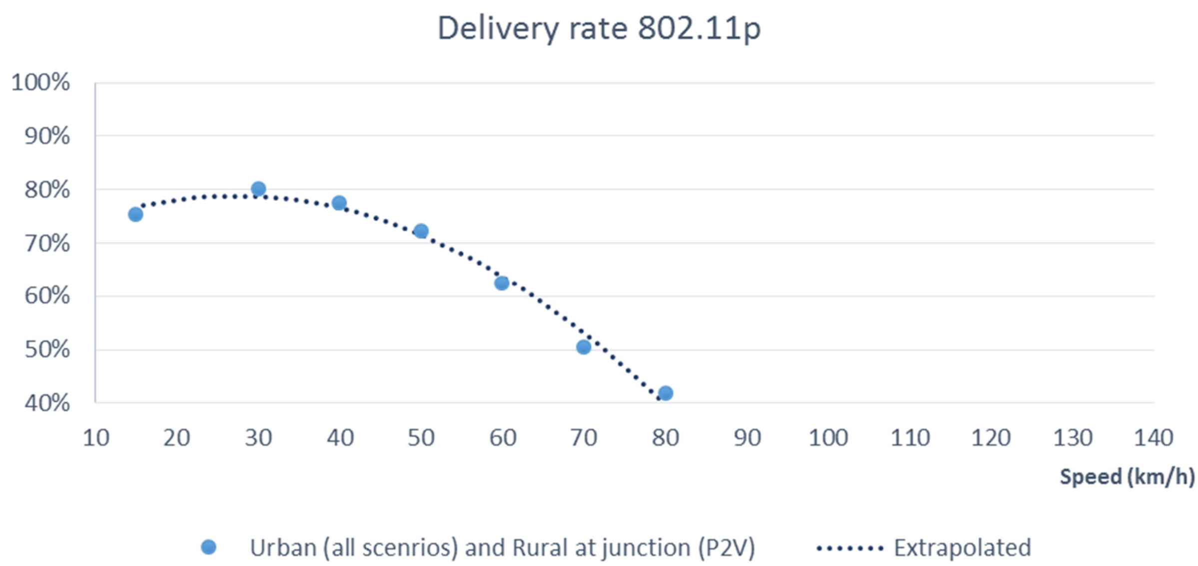
Note: Average over 50-100 km/h for rural V2P.

Figure 48: 802.11p alert delivery reliability – junction model – urban V2V



Note: Average over 15-40 km/h for urban at junction V2V/V2M. Average over 50-80 km/h for V2V/V2M rural at junction. Average over 20-60 km/h for urban not at junction V2V/V2M.

Figure 49: 802.11p alert delivery reliability – junction model – urban V2P



Note: Average over 15-40 km/h for urban V2P. Average over 50-80 km/h for rural V2P. Average over 20-60 km/h for urban V2P not at junction.

The averaging of the reliability rates in Figure 42 to Figure 49 above over the appropriate ranges of speeds results in the alert delivery reliability rates used to represent the radio performance of LTE-PC5 and 802.11p for the accident scenarios modelled in this report. These are presented in Table 17 and Table 18 below.

Table 17: Alert delivery reliability rates for LTE-PC5

LTE-PC5	At junction		Not at junction	
V2	Urban	Rural	Urban	Rural
Pedestrian	95.7%	67.3%	88.37%	98.40%
Vehicles	95.7%	82.5%	95.59%	99.37%

Table 18: Alert delivery reliability rates for 802.11p

802.11p	At junction		Not at junction	
V2	Urban	Rural	Urban	Rural
Pedestrian	78.00%	58.60%	74.80%	96.50%
Vehicles	78.00%	65.70%	80.70%	98.00%

Note that while a rigorous assessment of alert reliability could – in principle – be conducted for all crash avoidance scenarios, this is not viable in practice. Also, packet delivery delay is subject to congestion control protocols and more specifically to the particular implementation of alert algorithms. On-board alert algorithms have specific designs and vary with implementation. Absent the ability to model such levels of variability and detail, as an appropriate first order estimate we directly equate the packet reception ratio to the reliability of alert delivery.

C Results

This annex contains a list of tables with the results expressed as numbers of fatalities and serious injuries avoided.

Table 19: Number of annual fatalities avoided in red signal violation case

	Annual fatalities avoided Red Signal Violation case					
	LTE-V2X High	LTE-V2X Low	802.11p High	802.11p Low	LTE-Uu High	LTE-Uu Low
2007	0	0	0	0	0	0
2008	0	0	0	0	0	0
2009	0	0	0	0	0	0
2010	0	0	0	0	0	0
2011	0	0	0	0	0	0
2012	0	0	0	0	0	0
2013	0	0	0	0	0	0
2014	0	0	0	0	0	0
2015	0	0	0	0	0	0
2016	0	0	0	0	0	0
2017	0	0	0	0	0	0
2018	0	0	0	0	0	0
2019	0	0	0	0	0	0
2020	0	0	0	0	0	0
2021	0	0	0	0	2	0
2022	1	0	1	0	6	0
2023	4	1	3	0	12	1
2024	9	3	7	1	21	4
2025	18	7	15	3	33	8
2026	29	13	24	6	48	14
2027	43	21	35	9	65	22
2028	59	30	48	15	85	32
2029	77	42	63	22	106	45
2030	98	57	80	32	129	61
2031	120	74	98	45	154	80
2032	144	94	118	60	181	101
2033	170	116	140	77	208	122
2034	198	139	162	95	230	145
2035	225	163	185	115	248	168
2036	252	181	207	132	263	187
2037	271	203	222	153	273	208
2038	276	223	226	173	273	227
2039	276	243	226	193	273	246
2040	276	253	226	206	273	255

Table 20: Number of annual serious injuries avoided in red signal violation case

	Annual serious injuries avoided Red Signal Violation case					
	LTE-V2X High	LTE-V2X Low	802.11p High	802.11p Low	LTE-Uu High	LTE-Uu Low
2007	0	0	0	0	0	0
2008	0	0	0	0	0	0
2009	0	0	0	0	0	0
2010	0	0	0	0	0	0
2011	0	0	0	0	0	0
2012	0	0	0	0	0	0
2013	0	0	0	0	0	0
2014	0	0	0	0	0	0
2015	0	0	0	0	0	0
2016	0	0	0	0	0	0
2017	0	0	0	0	0	0
2018	0	0	0	0	0	0
2019	0	0	0	0	0	0
2020	0	0	0	0	0	0
2021	3	0	2	0	19	0
2022	14	0	11	0	67	0
2023	45	13	37	5	146	14
2024	107	41	88	15	255	45
2025	213	88	175	34	397	94
2026	348	156	286	66	571	166
2027	513	247	421	113	778	263
2028	705	364	579	178	1018	389
2029	924	509	759	268	1271	546
2030	1170	684	961	388	1549	738
2031	1438	890	1181	542	1847	966
2032	1729	1127	1420	724	2167	1209
2033	2044	1389	1678	927	2501	1468
2034	2372	1667	1948	1144	2759	1743
2035	2702	1951	2218	1377	2979	2021
2036	3025	2177	2483	1584	3155	2238
2037	3249	2438	2667	1831	3271	2491
2038	3306	2682	2714	2078	3274	2726
2039	3306	2920	2713	2320	3277	2955
2040	3306	3036	2713	2468	3280	3060

Table 21: Number of annual fatalities avoided in VRU case

	Annual fatalities avoided VRU case					
	LTE-PC5 High	LTE-PC5 Low	802.11p High	802.11p Low	LTE-Uu High	LTE-Uu Low
2007	0	0	0	0	0	0
2008	0	0	0	0	0	0
2009	0	0	0	0	0	0
2010	0	0	0	0	0	0
2011	0	0	0	0	0	0
2012	0	0	0	0	0	0
2013	0	0	0	0	0	0
2014	0	0	0	0	0	0
2015	0	0	0	0	0	0
2016	0	0	0	0	0	0
2017	0	0	0	0	0	0
2018	0	0	0	0	0	0
2019	0	0	0	0	4	0
2020	0	0	0	0	64	0
2021	0	0	0	0	167	5
2022	0	0	0	0	311	26
2023	18	0	0	0	465	76
2024	81	0	0	0	621	170
2025	220	0	0	0	774	309
2026	434	0	0	0	930	454
2027	704	0	0	0	1086	604
2028	943	0	0	0	1243	760
2029	1156	0	0	0	1383	924
2030	1350	0	0	0	1519	1098
2031	1527	0	0	0	1649	1278
2032	1695	0	0	0	1776	1443
2033	1856	0	0	0	1893	1596
2034	2005	0	0	0	1941	1739
2035	2134	0	0	0	1958	1863
2036	2243	0	0	0	1945	1967
2037	2309	0	0	0	1932	2051
2038	2333	0	0	0	1918	2110
2039	2316	0	0	0	1905	2158
2040	2300	0	0	0	1891	2195

Table 22: Number of annual serious injuries avoided in VRU case

	Annual serious injuries avoided VRU case					
	LTE-PC5 High	LTE-PC5 Low	802.11p High	802.11p Low	LTE-Uu High	LTE-Uu Low
2007	0	0	0	0	0	0
2008	0	0	0	0	0	0
2009	0	0	0	0	0	0
2010	0	0	0	0	0	0
2011	0	0	0	0	0	0
2012	0	0	0	0	0	0
2013	0	0	0	0	0	0
2014	0	0	0	0	0	0
2015	0	0	0	0	0	0
2016	0	0	0	0	0	0
2017	0	0	0	0	0	0
2018	0	0	0	0	0	0
2019	0	0	0	0	52	0
2020	0	0	0	0	767	0
2021	0	0	0	0	2005	65
2022	0	0	0	0	3736	315
2023	216	0	0	0	5580	907
2024	977	0	0	0	7448	2045
2025	2641	0	0	0	9293	3711
2026	5205	0	0	0	11155	5453
2027	8451	0	0	0	13030	7246
2028	11322	0	0	0	14920	9122
2029	13876	0	0	0	16598	11092
2030	16199	0	0	0	18234	13171
2031	18324	0	0	0	19787	15338
2032	20338	0	0	0	21306	17319
2033	22270	0	0	0	22713	19156
2034	24059	0	0	0	23292	20869
2035	25611	0	0	0	23496	22356
2036	26914	0	0	0	23342	23606
2037	27704	0	0	0	23184	24606
2038	27993	0	0	0	23022	25322
2039	27792	0	0	0	22856	25896
2040	27597	0	0	0	22695	26337

D Result charts presenting fatalities only

This annex presents charts showing the impacts of the different communication solutions on EU road fatalities, to complement the results for fatalities and serious injuries in the main text.

Figure 50 and Figure 51 show annual fatalities for the red signal violation case under the high and low scenarios, respectively.

Figure 50: Red signal violation - Total annual fatalities in the high scenario for the three C-ITS communication solutions in comparison to the baseline.

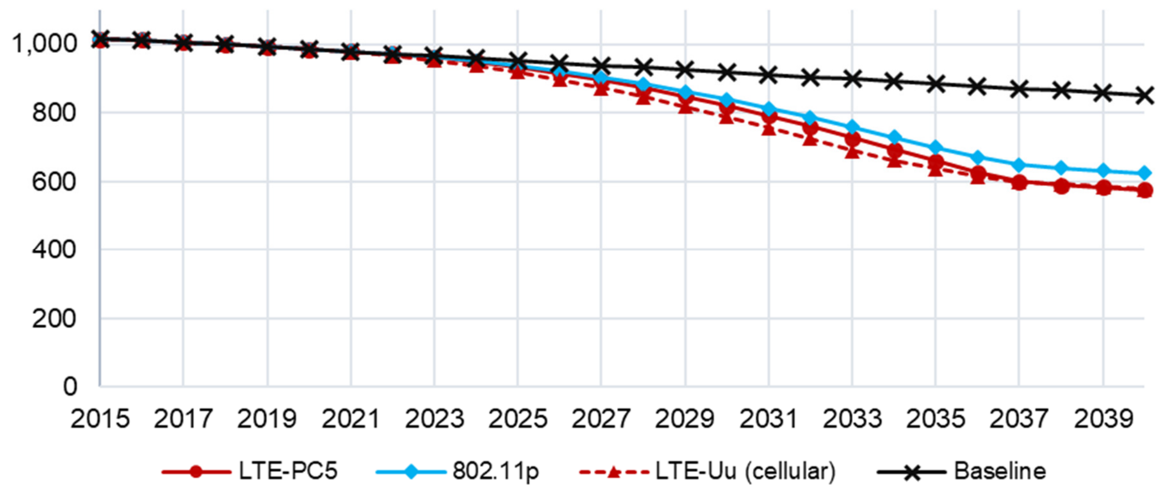


Figure 51: Red signal violation - Total annual fatalities in low scenario for the three C-ITS communication solutions in comparison to the baseline.

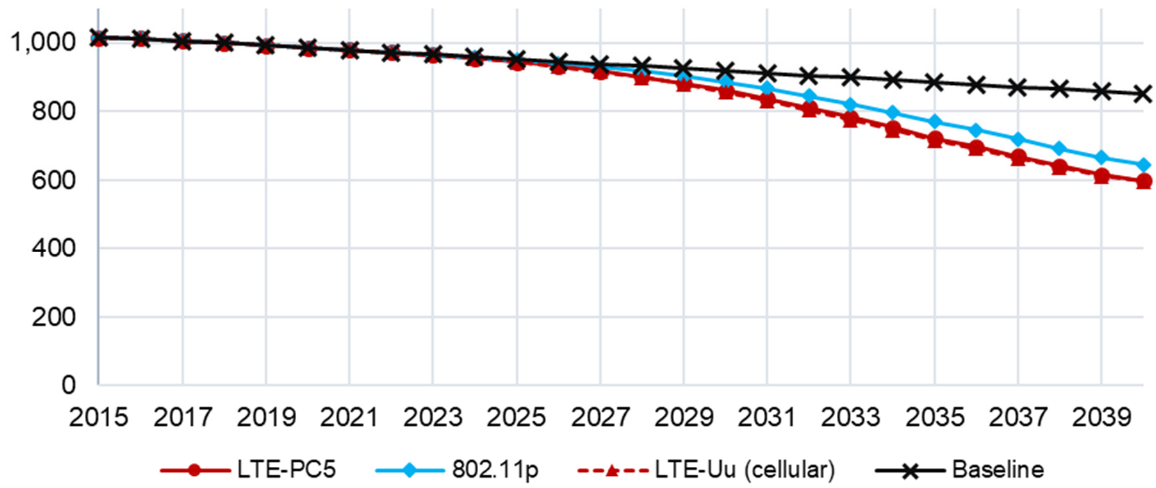


Figure 52 and Figure 53 show annual fatalities for the VRU protection case under the high and low scenario, respectively.

Figure 52: VRU protection - Total annual fatalities in the high scenario for the three C-ITS communication solutions in comparison to the baseline.

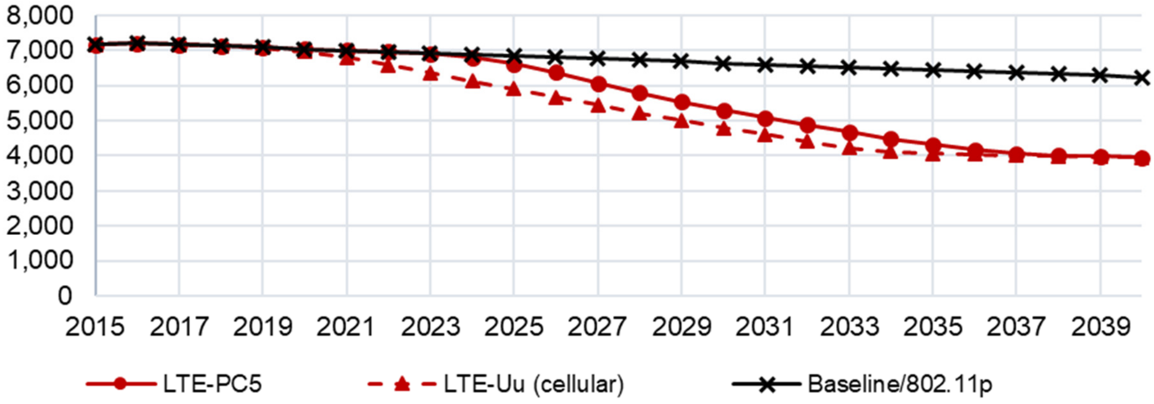


Figure 53: VRU protection - Total annual fatalities in the low scenario for the three C-ITS communication solutions in comparison to the baseline.

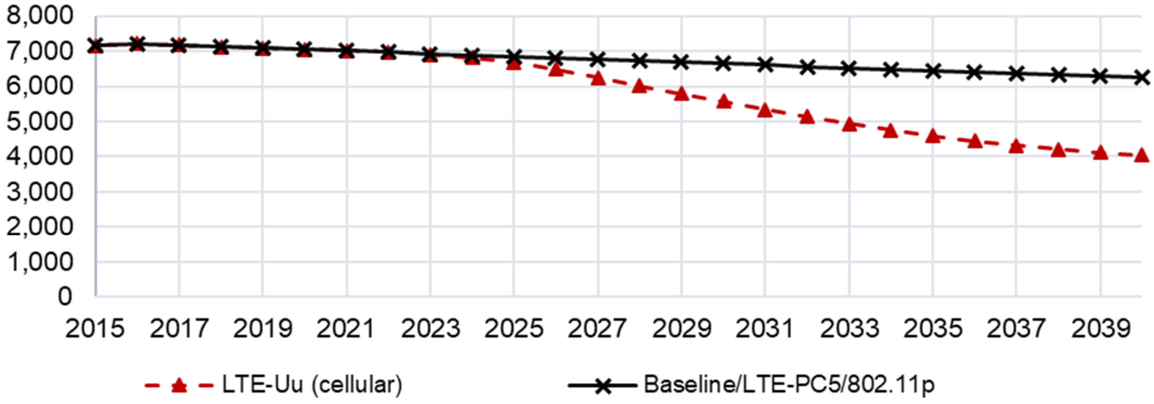


Figure 54 and Figure 55 show aggregated results for both use cases without retrofitting under the high and low scenario, respectively.

Figure 54: Aggregated results for both use cases in the high scenario- Cumulative avoided fatalities - Without retrofitting

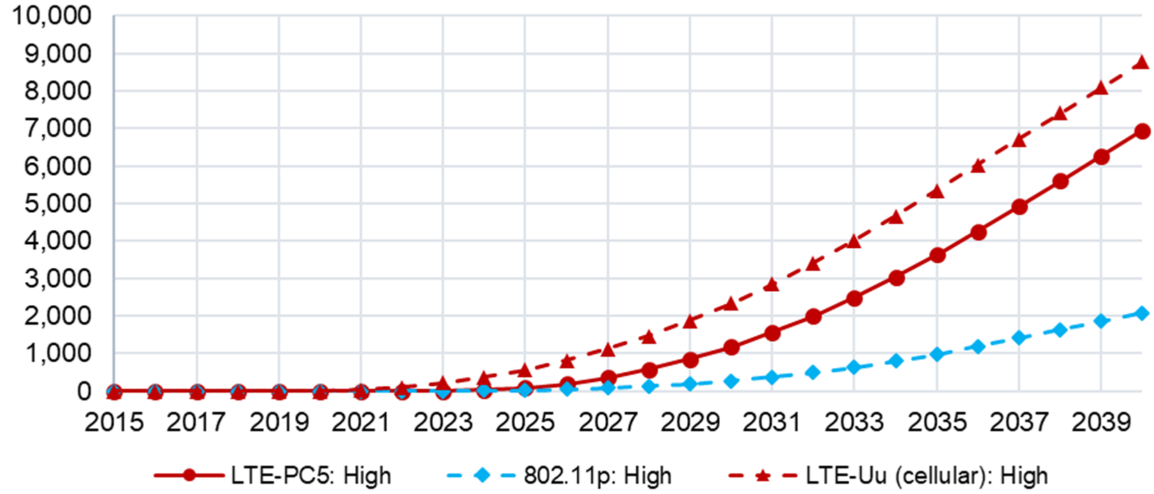
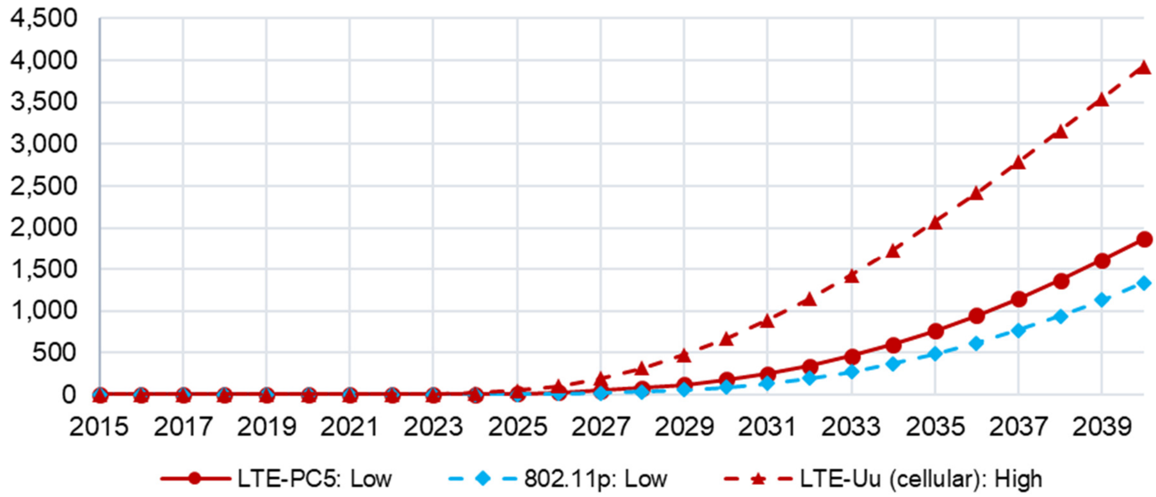


Figure 55: Aggregated results for both use cases in the <u>low</u> scenario- Cumulative avoided fatalities - Without retrofitting



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