5GAA
Automotive Association

# An assessment of LTE-V2X (PC5) and 802.11p direct communications technologies for improved road safety in the EU

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# Executive Summary

This report presents a quantitative analysis of the ability of Cooperative Intelligent Transport Systems (C–ITS) using short-range *ad hoc*/direct communications to reduce the number of fatalities and serious injuries caused by motoring accidents in the EU.

Specifically, two standardised C-ITS short-range technologies are compared for the purposes of this report, namely **3GPP LTE-V2X PC5** (also known as LTE side-link) and **IEEE 802.11p** (also known as DSRC[1] or ITS-G5), both operating in the 5.9 GHz band for the provision of *direct* communications between road users. It should be noted that additional reductions in the number of fatalities and serious injuries are possible via longer-range C-ITS communications enabled through interactions with a LTE cellular network, but that these are not considered in this report. Hence, the analysis is limited to LTE-V2X (PC5) only, in comparison to 802.11p.

LTE-V2X[2] was standardised by the 3GPP in 2016 under the umbrella of LTE Release 14 and encompasses two interfaces: (a) a wide area network LTE interface (Uu) that connects end-user devices and vehicles to mobile network base stations and mobile core networks, for provision of Internet and vehicle to network (V2N) services; and (b) a *direct* communications interface (PC5) that connects vehicles to vehicles (V2V), to roadside infrastructure (V2I) and to pedestrians and other vulnerable road users (V2P), for provision of low-latency and high-reliability vehicular services. The LTE-V2X (PC5) interface does not necessarily require assistance from a mobile network.

802.11p is an extension of 802.11a (Wi-Fi), and was standardised by the IEEE in 2009. In 2012, 802.11p was included in the overall IEEE 802.11 standard, but the informal term, 802.11p, is in general use. The 802.11p multiple access mechanism (Carrier Sense Multiple Access protocol with Collision Avoidance, CSMA-CA) is a statistical protocol for *direct* communications and connecting vehicles to vehicles (V2V) and to roadside infrastructure (V2I).

This study examines and compares two independent counter-factual scenarios: one where LTE-V2X (PC5) is the only deployed C-ITS technology, and another where 802.11p is the only deployed C-ITS technology.

We consider, as a baseline, the existing and future projected statistics for road traffic fatalities and serious injuries in the EU. We then evaluate the reduction in the number of fatalities and serious injuries which may occur as a result of C-ITS direct communications between road users, by modelling:

i) The expected take-up (penetration) of LTE-V2X (PC5) and 802.11p among road users in the EU over time (including vehicles, motorcycles, bicycles and pedestrians), and

ii) the radio link performance of LTE-V2X (PC5) and 802.11p in successfully delivering actionable warning messages between road users in a number of collision scenarios.

To account for the uncertainty in predicting the extent of future deployment of short-range C-ITS technologies, we have developed "high" and "low" scenarios for the penetrations of LTE-V2X (PC5) and 802.11p among road users. The "high" scenario assumes equal and aggressive levels of penetration for the two technologies in vehicles and motorcycles. The "low" scenarios represent more pessimistic outlooks for the penetrations of the two technologies, and are derived from publicly available sources. The "high" case also accounts for the penetration of LTE-V2X (PC5) in smartphones, which additionally enables the protection of vulnerable road users (VRUs), namely pedestrians and cyclists.

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[1] Dedicated short range communications

[2] LTE-V2X is today's realisation of what the 5GAA broadly refers to as Cellular-V2X (C-V2X).

The analysis of radio link performance indicates that the likelihood of successful delivery of warning messages between two road users equipped with LTE-V2X (PC5) is greater than it is for the case of two road users equipped with 802.11p. The calculated likelihoods are indicated below for the case of vehicle/vehicle collisions. Likelihoods are also calculated for vehicle/motorcycle, vehicle/bicycle and vehicle/pedestrian collisions.

| | Likelihood of successful delivery of warning messages between two vehicles | | | | | |
|---|---|---|---|---|---|---|
| | At a junction | | | Not at a junction | | |
| | Urban | Rural | Motorway | Urban | Rural | Motorway |
| LTE-V2X (PC5) | 96% | 83% | N/A | 96% | 99% | 94% |
| 802.11p | 78% | 66% | N/A | 81% | 98% | 86% |

Overall, the modelling indicates that the deployment of LTE-V2X (PC5) would avoid greater numbers of fatalities and serious injuries on the EU's roads than would be the case for 802.11p. The cumulative statistics by the year 2040 are presented below.

| Time-frame: 2018-2040 | Avoided fatalities | | Avoided serious injuries | |
|---|---|---|---|---|
| | High | Low | High | Low |
| LTE-V2X (PC5) | 59,000 | 29,000 | 660,000 | 275,000 |
| 802.11p | 39,000 | 20,000 | 360,000 | 180,000 |

We caveat the above results by noting that even the modelled "low" 802.11p penetration is expected to be overly optimistic, given that – at the time of writing – only a single European car vendor has announced an intention to deploy 802.11p, expected from 2019. Whereas, the modelled "low" LTE-V2X (PC5) penetration is based on the on-going growth in the availability of LTE modems in vehicles (currently included for purposes such as telematics and infotainment), and what we consider to be a realistic future projection of PC5 functionality in such LTE modems.

We identify the following conclusions and recommendations from the results of this report:

- The study indicates that LTE-V2X (PC5) outperforms 802.11p in reducing fatalities and serious injuries on the EU's roads. This is due to a combination of the superior performance of LTE-V2X (PC5) at the radio link level for *ad hoc*/direct communications between road users, and the market led conditions which better favour the deployment of LTE-V2X in vehicles and in smartphones, and include a clear evolutionary path towards 5G-V2X. **For these reasons, it is essential that EU regulations remain technology neutral and do not hinder the deployment of LTE-V2X (PC5) in favour of 802.11p for the provision of direct communications among vehicles and between vehicles and vulnerable road users.**

- An absence of interoperability at radio link level between LTE-V2X (PC5) and 802.11p is unlikely to present a substantive barrier to the reduction of road accidents in the EU in the short to medium term. The relatively low penetration of C-ITS technologies in vehicles in the first half of the next decade (and perhaps even later) means that a vehicle equipped with LTE-V2X (PC5) or 802.11p is far more likely to collide with a vehicle that is not equipped with C-ITS technologies at all – indeed it is not until the middle of the next decade that penetration rates are expected to reach a level which results in significant impacts on accident rates. **Any regulations which mandate LTE-V2X (PC5) to be backward interoperable with 802.11p will therefore have only a limited effect in the early years of deployment pre-2025. Such regulations will run the risk of unnecessarily distorting the market in favour of 802.11p, thereby obstructing the adoption of LTE-V2X (PC5) and resulting in greater road fatalities and injuries in the longer term.**

# Contents

# Glossary

| | |
|---|---|
| **3GPP** | 3rd Generation Partnership Project |
| **4G** | Fourth Generation Wireless Broadband |
| **5G** | Fifth Generation Wireless Broadband |
| **5GAA** | 5G Automotive Alliance |
| **802.11p** | IEEE standard for direct communication between road users and with roadside infrastructure |
| **CARE** | Community Road Accident Database |
| **C-ITS** | Co-operative Intelligent Transport Systems |
| **DfT** | Department for Transport |
| **DRIVE-C2X** | DRIVing implementation and Evaluation of C2X communication technology in Europe |
| **DSRC** | Dedicated Short Range Communications |
| **IEEE** | Institute of Electrical and Electronics Engineers |
| **ITS** | Intelligent Transport Systems |
| **LTE** | Long-Term Evolution |
| **LTE-V2X** | 3GPP standard for vehicle-to-everything communication |
| **LTE-V2X (PC5)** | Interface for direct communication between road users and with roadside infrastructure |
| **LTE-V2X (Uu)** | Interface for communication between vehicles and mobile network |
| **OEM** | Original Equipment Manufacturer |
| **SVCs** | Single Vehicle Collisions |
| **V2I** | Vehicle-to-Infrastructure |
| **V2M** | Vehicle-to-Motorcycle |
| **V2N** | Vehicle-to-Network |
| **V2P** | Vehicle-to-Pedestrian (in this report this also includes cyclists) |
| **V2V** | Vehicle-to-Vehicle |
| **V2X** | Vehicle-to-Everything |
| **VRU** | Vulnerable Road User |

# 1 Introduction and overview

## 1.1. Introduction

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 [1], these improvements are likely to be 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 [2]. This is particularly relevant given the slow-down observed in the reduction of fatalities on EU roads over the last three years, with the yearly improvement trending from an annual reduction of 6% between 2006 and 2010 to just 2% from 2011 to 2015. The European Commissioner for Transport, Violeta Bulc, commented in the 2017 Malta road safety conference:

*''Today's statistics are an improvement and something positive to build on. But it's not the figures that worry me the most – it's the lives lost, and the families left behind. Just today we will lose another 70 lives on EU roads and five-times as many will sustain serious injuries! I'm inviting all stakeholders to step up their efforts so we can meet the objective of halving the number of road deaths between 2010 and 2020''.*

Intelligent Transport Systems (ITS) have been identified by both public and private sector stakeholders as having major potential to help achieve the societal goal of improving road safety. One of the seven strategic objectives of the Road Safety Programme is to "boost smart technology" such that data and information can be easily exchanged between vehicles, between vehicles and infrastructure and between vehicles and vulnerable road users (VRUs) such as cyclists and pedestrians. [2]

Co-operative Intelligent Transport Systems (C-ITS) in particular provide services that improve road safety and decrease both the number and the severity of accidents. Such services include for example hazardous location warnings, in-vehicle speed limit displays, and alerts to improve intersection safety.

Two key technologies are available to enable C-ITS services through direct communications between road users: 3GPP LTE-V2X (PC5) and IEEE 802.11p. These two technologies are permitted to operate in the so-called "5.9 GHz" band (5875-5905 MHz) which has been harmonised – in a technology neutral manner – for safety-related applications of ITS in Europe[3].

Whilst a technology neutral approach enabling both LTE-V2X (PC5) and 802.11p to be used in the 5.9GHz band is favoured by some in the European Commission, a number of questions remain, specifically relating to interoperability, compatibility, and other aspects. Nevertheless, LTE-V2X has a number of advantages over 802.11p, including its ability to also provide (via its Uu interface) longer-range vehicle-to-network (V2N) communications, leveraging use of the commercial mobile telecommunications network spectrum to enable connections to cloud-based infrastructure and back-office systems, and utilising the existence of extensive mobile infrastructure along the EU road networks. Furthermore, its scalability and ability to evolve as mobile communications develop (e.g. the transition from 4G to 5G) are seen as significant benefits of LTE-V2X. At the same time, LTE-V2X (via its PC5 interface) is also able to provide direct V2V communications between devices, with no subscription or network intervention required, and with improved performance relative to 802.11p.

The 5G Automotive Alliance (5GAA) has developed a model to assess the relative performance of the LTE-V2X (PC5) and 802.11p technologies with regards to improving road safety in the EU, focusing on direct V2X communications in the 5.9GHz spectrum. This report sets out the findings of this research. Note that the analysis presented in this report excludes any benefits of V2I or other long-range

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[3] An extension to 5905-5925 MHz is under consideration.

communications. The modelling underlying this report has been peer-reviewed and validated in detail by the technology and policy consultancy, Ricardo.

## 1.2. Overview of this report

The objective of the report is to assess the relative performance of LTE-V2X (PC5) and 802.11p communication technologies in improving road safety in the EU based on the numbers of fatalities and serious injuries that can be avoided through direct device-to-device communication. Note that the two technologies are considered in isolation; i.e., either in a world with no 802.11p or in a world with no LTE-V2X. This study does not therefore take account of any interoperability or compatibility matters, but rather serves to illustrate the relative merits of each technology considered in isolation.

The remainder of the report is structured as follows:

- Section 2 – Provides an overview of the modelling methodology including a discussion of the input data and modelling assumptions.
- Section 3 – Discusses the modelling results, presenting the estimated number of accidents avoided due LTE-V2X (PC5) and 802.11p technologies.
- Section 4 – Provides conclusions on the effectiveness of the two technologies in reducing road accidents, presents recommendations on regulations in the EU.

Data sources used for the modelling are presented in the References section. The annexes provide details on the modelling assumptions and input data as well as disaggregated results.

# 2 Modelling methodology

## 2.1. Outline

To quantify the number of collisions that can be avoided through the use of device-to-device C-ITS communications technologies, our starting point has been to analyse the accident statistics released by the European Commission. This is in order to establish a *baseline* for the existing and future number of fatalities and serious injuries by year, type of road and mode of transport, in the absence of C-ITS.

Once the baseline is defined, the effectiveness of LTE-V2X (PC5) and 802.11p can be evaluated. Specifically, the number of fatalities and serious injuries that could be avoided through the use of C-ITS technologies can be written as

$$N_{Avoid}(t) = N_{Base}(t) P_{C-ITS}(t) F_{Mit} D_{C-ITS}\, E \tag{1}$$

where

- $N_{Avoid}(t)$ is the number of fatalities or serious injuries that can be avoided in year $t$ through the use of C-ITS technologies.
- $N_{Base}(t)$ is the baseline number of fatalities or serious injuries that would occur in year $t$ in the absence of C-ITS technologies.
- $P_{C-ITS}(t)$ is the likelihood in year $t$ that any two road users (vehicles, motorcycles or VRUs[4]) involved in a potential accident will both be equipped with the same C-ITS technology allowing direct device-to-device (V2V/V2P) communications. This is calculated by multiplying together the two penetration rates of the considered C-ITS technology among the populations of the two respective road user types (vehicles, motorcycles or VRUs) involved in a potential collision.
- $F_{Mit}$ is the fraction of fatalities or serious injuries which can be addressed and mitigated by the considered C-ITS technology. This factor is maintained constant in time.
- $D_{C-ITS}$ is the alert/warning delivery reliability; i.e., the likelihood that data transmitted from a vehicle/motorcycle/VRU via a C-ITS technology is successfully communicated to its intended recipient. This factor is maintained constant in time.
- $E$ is the effectiveness of a received alert/warning message in appropriately affecting the behaviour of the driver of a vehicle travelling towards a potential accident; i.e. the likelihood that the driver is able to react and avoid the accident. This factor is maintained constant in time.

Further details on the calculation of the above parameters can be found in the next section, and in the annexes.

Figure 1 shows an overview of the modelling methodology developed to perform the analysis, including key inputs and outputs.

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[4] Note: VRUs are considered to consist of pedestrians and cyclists for the purposes of this report. Motorcycles have not been classified as VRUs but as a separate vehicle category. The distinction is that motorcycles are assumed to have a dedicated antenna for using C-ITS technologies, whereas VRUs are modelled as using C-ITS technologies via their smartphones.

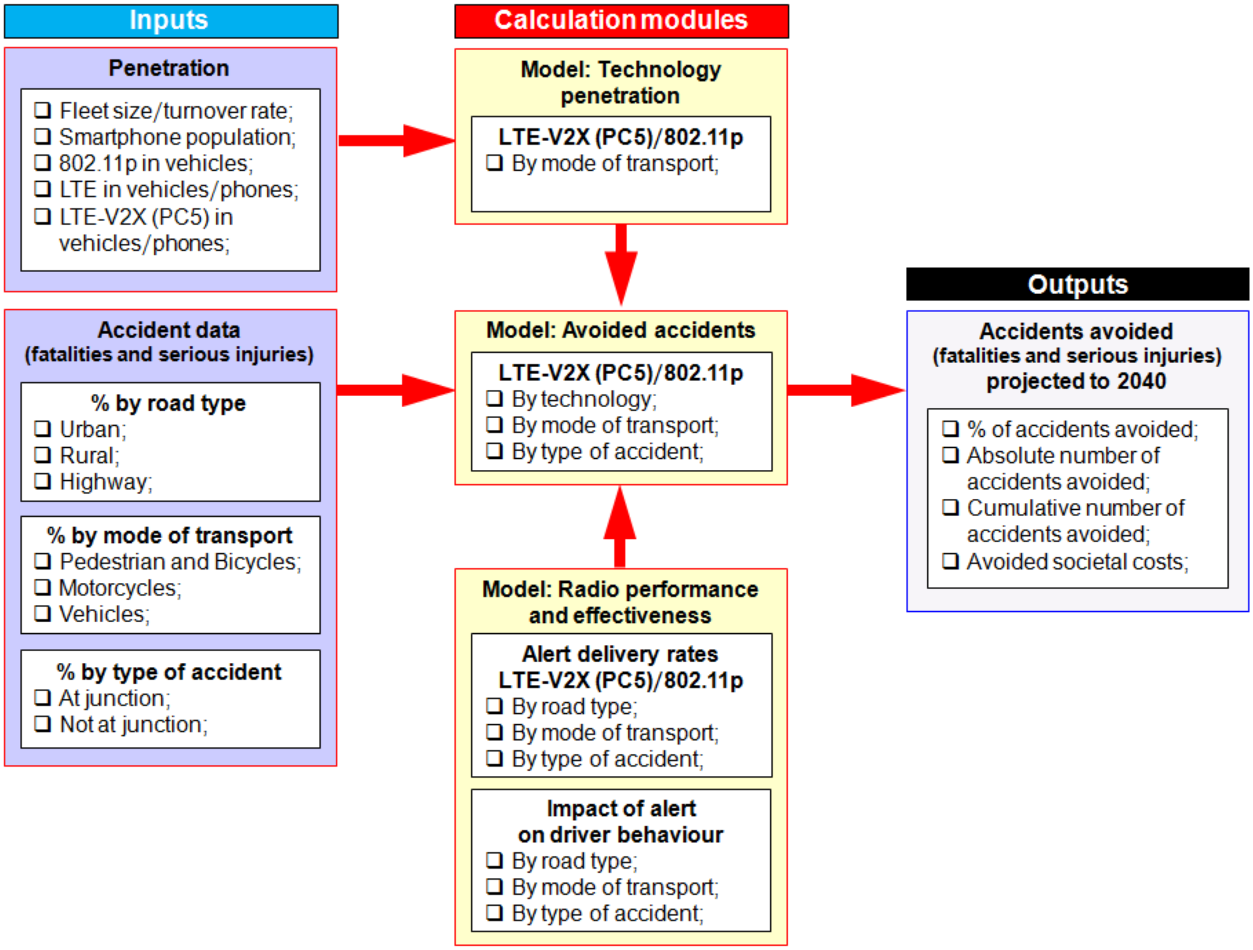

*Figure 1: Overview of the modelling methodology.*

In order to appropriately assess the performance of LTE-V2X (PC5) and 802.11p in the context of reliable delivery of life-critical alerts to avoid collisions, scenarios based on different road types, modes of transport modes and types of accidents have been modelled, given that the effectiveness of C-ITS technologies in urban, motorway or rural scenarios and between different modes of transport is expected to be different.

For example, urban fatalities are disaggregated by modes of transport; i.e., vehicle to pedestrian/cyclist (V2P), vehicle to motorcycle (V2M) and vehicle to vehicle (V2V), and according to whether they happen at a junction or not. A summary of the different modelling scenarios is provided in Table 1.

*Table 1: Summary of modelling scenarios.*

| | Category | Definition |
|---|---|---|
| Road type | Urban | A definition based on speeds has been applied. Motorways are modelled considering speeds of 70 – 140 km/h, rural roads are modelled with speeds of 50 – 100 km/h and urban roads with speeds of 60 km/h or less. |
| | Rural | |
| | Motorway | |
| Mode of transport | Pedestrians and cyclists | Pedestrians and cyclists are modelled as “smartphone users”, with the alert delivery reliability for those users modelled accordingly. Penetration of the C-ITS technology in smartphones and the penetration of smartphones in the population are incorporated into the analysis. |
| | Motorcycles | This category includes motorcycles and mopeds, with the same alert delivery reliability as for the vehicles category. |
| | Vehicles | This category includes cars, heavy duty trucks, vans and buses. |
| Type of accident | At junctions | The following speed ranges are used to model accidents at junctions:<br>Urban: 15 – 40 km/h<br>Rural: 50 – 80 km/h<br>Motorways: not modelled |
| | Not at junctions | The following speed ranges are used to model accidents where junctions are not involved:<br>Urban: 20 – 60 km/h<br>Rural: 50 – 100 km/h<br>Motorways: 70 – 140 km/h |

## 2.2. Key assumptions

This section describes the five terms that are included in Equation (1) presented earlier.

### 2.2.1. Baselines for fatalities and serious injuries

Accident statistics (CARE data) released by the European Commission are available for the period 2006 to 2015 [3] and can be used as a baseline for the number of fatalities and serious injuries in the absence of C-ITS technologies.

In order to perform an analysis for future years, we have derived baselines for the period 2016 to 2040. Historically, the overall number of fatalities has decreased over time, but improvements have stagnated in recent years. Consequently, we have used the trend of data over the last two years (2014-2015) to extrapolate the number of fatalities over the time period post-2015. It should be pointed out that this extrapolation would include single-vehicle accidents which cannot be readily avoided via C-ITS technologies for *ad hoc*/direct communications. A study from the European Transport Safety Council [4] estimates that a third of road fatalities in the EU are due to single vehicle collisions (SVCs). These fatalities have therefore been removed from the CARE statistics to obtain the baseline illustrated in Figure 2. A similar trend is applied to the number of serious injuries. See Table 4 and Table 5 in Annex A respectively for the extrapolated numbers of fatalities and serious injuries up to the year 2040.

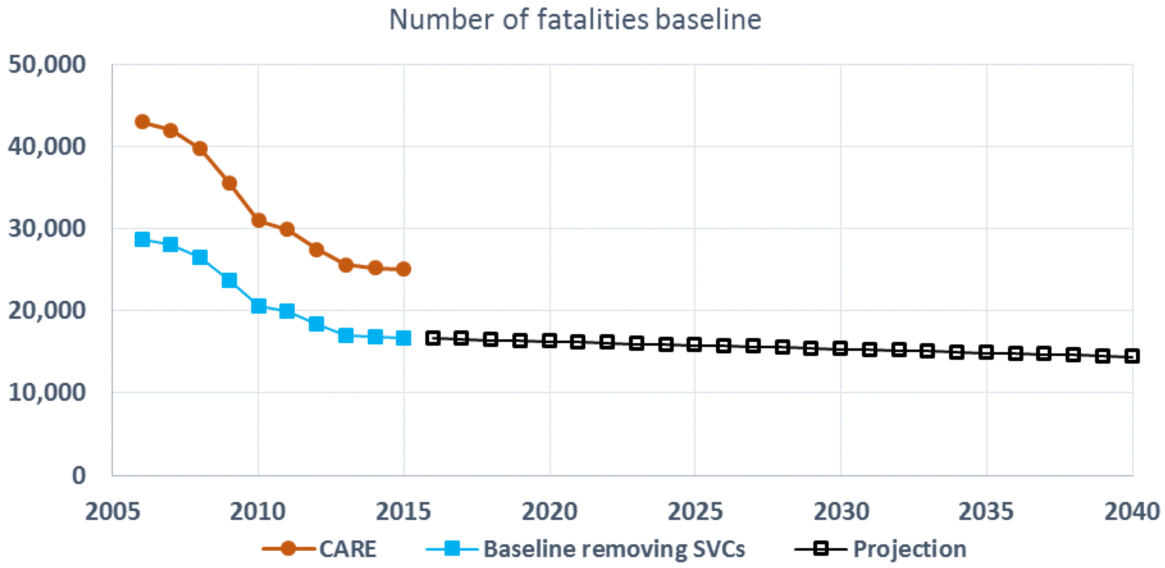

*Figure 2: Baseline number of fatalities extrapolated from Eurostat (CARE) data.*

Note that the baseline does not account for the impacts of long-range cellular communications (via mobile networks), or indeed technologies other than C-ITS, in reducing the number of accidents. As such, the estimates presented in this report represent an upper bound on the number of fatalities and serious injuries which might be avoided via LTE-V2X (PC5) or 802.11p short-range communications.

In order to correctly assess the impact of C-ITS in reducing accidents on different types of roads, we have analysed the breakdown of fatalities and serious injuries by road type [3][16]. These are shown in Figure 8 in Annex A.

As described in the following sections, alert delivery reliability rates are modelled differently for vehicles and smartphones, where the latter are considered for the case of VRUs (pedestrians/cyclists). For this reason, we have further considered a breakdown of the baseline figures by mode of transport. The percentage splits of the number of fatalities and serious injuries by transport mode and road type are provided in Table 6 and Table 7 in Annex A.

Finally, the number of accidents are split into accidents which occur at junctions and those which occur elsewhere, as shown in Table 8 of Annex A.

### 2.2.2. Squared probability

This is the probability that any two road users (vehicles, motorcycles or VRUs) involved in a potential collision will *both* be equipped with the same C-ITS technology for direct communications.

We refer to this as a “squared probability” because it is calculated as the product of the penetration of the relevant C-ITS technology across the entire population of the first road user (vehicle, motorcycle or VRU) involved in a potential accident, multiplied by the penetration of the same C-ITS technology across the entire population of the second road user (vehicle, motorcycle or VRU) involved in the said accident. The higher the levels of market penetration, the greater the probability that the two road users involved in a potential collision will be equipped with the same C-ITS technology.

To model the penetration of a C-ITS technology across the entire fleets of vehicles and motorcycles in the EU, it is necessary to evaluate the total size of these fleets, as well as the number of new vehicles and motorcycles entering the respective fleets over time. These have been extracted from Eurostat [5]. Growth rates have been obtained from a separate transport sector analysis carried out by Ricardo (see Table 9, Annex B). To account for vehicles leaving the EU fleet in future years, a lifetime of 14 years has been assumed for all vehicle types, except for motorcycles where a lifetime of 17 years has been used. Table 10 in Annex B shows the modelled statistics for the total size of the fleets and the number of new vehicles and motorcycles entering the EU market up to year 2040.

To model the penetration of LTE-V2X (PC5) among the population of VRUs (pedestrians and cyclists), we use the penetration of LTE-V2X (PC5) in smartphones as a proxy. For this purpose, we have obtained data from Statista ( [6] and [7]) on the current rates of penetration of smartphones among the general population in Central/Eastern and Western Europe (see Table 13, Annex B). Future projections for the penetration rates of smartphones across the entire EU population have been developed based on projections of EU population age distribution [8] (Table 14, Annex B).

A key element in modelling the penetration of a C-ITS communications technology across the entire fleet of vehicles, motorcycles or VRUs is the penetration of the said technology among *new* vehicles, motorcycles or smartphones entering the market over time. To account for the inevitable uncertainties involved in predicting such future penetrations, we have developed two scenarios:

- **Low scenario** based on data from publicly available sources – with differing penetration rates applied to LTE-V2X (PC5) and 802.11p, thereby allowing a comparison of the impact of differential uptake rates for the two technologies over time in vehicles and motorcycles. A zero penetration of C-ITS in smartphones (i.e., among VRUs) is assumed in this scenario.
- **High scenario** representing a case of aggressive deployment in vehicles and motorcycles – with the same penetration rates applied to LTE-V2X (PC5) and 802.11p in vehicles and motorcycles. Penetration of LTE-V2X (PC5) in smartphones (i.e. among VRUs) is also accounted for in this scenario. Note that the mobile equipment vendors in 5GAA do not foresee future deployments of 802.11p in smartphones. We have therefore applied a zero penetration of 802.11p in smartphones in this scenario.

Once again, it should be noted that the analysis does not assume any interoperability between the two technologies, and each technology is assessed in isolation. The above scenarios are described next.

#### Low scenario

In the low scenario, the current and projected future penetration rates for 802.11p in *new* cars have been analysed based on data obtained from Visiongain [9]. To adjust for the situation in the EU (C-ITS only becoming available from 2019) the timeline from the Visiongain report has been moved back by 4 years, with deployment starting in 2019 and reaching 100% penetration in new cars by 2032. See Figure 9, Annex B.

Note that despite the above adjustment, the modelled low scenario is expected to be overly optimistic particularly in the early years. This is because at the time of writing, only a single European car vendor has announced an intention to deploy 802.11p from 2019 [10].

For 802.11p in motorcycles, the same penetration trend is used; however, an additional delay of 5 years is assumed to account for the fact that motorcycle solutions are at an earlier stage of development. This might be an optimistic assumption, and greater delays may be possible.

The low scenario LTE-V2X (PC5) penetration rates have been estimated by considering a) the penetration of embedded and hybrid telematics provided by IHS Markit [11] and the share of LTE in embedded telematics provided by IHS Automotive [12], and b) the penetration of LTE-V2X (PC5) functionality in LTE chips.

Regarding the latter, it has been assumed that LTE chipsets equipped with 3GPP Release 14 PC5 functionality will begin to hit the market in 2018 [13] and that full penetration in all LTE-equipped devices in new vehicles will be achieved six years later. This is broadly consistent with the deployment growth of previous 3GPP releases. The resulting penetrations are shown in Table 11, Table 12 and Figure 10 in Annex B.

Again, a delay of 5 years is assumed for LTE-V2X (PC5) in motorcycles as compared to the case for vehicles.

In the low scenario, it is assumed that there will be no deployment of LTE-V2X (PC5) or 802.11p technology in smartphones. Therefore, the penetration of C-ITS in the context of the protection of VRUs is set to zero in this instance.

### High scenario

The high scenario assumes the same penetration in new vehicles for both LTE-V2X (PC5) and 802.11p, and represents an aggressive deployment characterised by rapid growth of C-ITS among road users. With deployments starting in 2019, it is assumed that most vehicle models will go through a refresh cycle over the following 6 year period, so that it can be expected that all *new* vehicles will be equipped by 2025. Specifically, the penetration in new cars is assumed to be 25% in 2022 (3 years after start of deployments, allowing for a slow initial ramp-up[5]), 50% in 2023, 75% in 2024, and 100% in 2025. See Figure 9 for 802.11p and Figure 11 for LTE-V2X (PC5), both in Annex B.

For LTE-V2X (PC5) and 802.11p in motorcycles, the same penetration trend as above is assumed; however, again an additional delay of 5 years is applied to account for the fact that motorcycle solutions are at an earlier stage of development.

The high scenario also accounts for the penetration of LTE-V2X (PC5) in smartphones, which additionally enables the protection of VRUs.

In this respect, we link the penetration of LTE-V2X (PC5) in new smartphones to the penetration of LTE-V2X (PC5) in vehicles. Specifically, the deployment of LTE-V2X (PC5) in smartphones is delayed until 2022 by which time the penetration of the technology in new vehicles is expected to reach 25%. This is considered sufficient to trigger demand for LTE-V2X (PC5) functionality in smartphones. A cap of 80% has been applied, assuming that 20% of the users who own a smartphone with LTE-V2X (PC5) functionality will not use it, for privacy or other reasons. The modelled penetration is shown in Figure 14 in Annex B.

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[5] The high scenario penetration in the first three years is lower bounded by the penetration that is assumed in the low scenario.

Note that the high and low scenarios described above refer to the modelling of the penetration of C-ITS in *new* vehicles, motorcycles, and smartphones. These need to be translated into corresponding penetrations in the entire fleets of vehicles and motorcycles, and the entire population of smartphones.

To obtain the penetration of C-ITS across the entire fleets of vehicles and motorcycles in the EU, the number of *new* vehicles and motorcycles equipped with C-ITS in each year are first calculated. This is performed by multiplying the number of new vehicles and motorcycles (see Table 10, Annex B) with the modelled penetrations of C-ITS in new vehicles and motorcycles (see Figure 9 and Figure 11, Annex B), respectively. The resulting cumulative numbers of new vehicles and motorcycles equipped with C-ITS (minus the number of vehicles and motorcycles that have reached the end of their life) are then divided by the number of vehicles and motorcycles in the entire fleet, respectively, to derive the fleet-wide C-ITS penetration rates. Figure 12 and Figure 13 in Annex B show the fleet-wide penetrations of LTE-V2X (PC5) and 802.11p over time for the high and low scenarios.

To obtain the penetration of LTE-V2X (PC5) across the entire population of VRUs, the modelled penetration rates of LTE-V2X (PC5) in new smartphones (Figure 14, Annex B) are multiplied with the percentage of the population who own a smartphone (Table 13, Annex B), accounting for a lifetime of two years for smartphones. Figure 15 of Annex B shows the resulting penetration of LTE-V2X (PC5) across all VRUs.

The modelled penetration rates across all road users for LTE-V2X (PC5) and 802.11p technologies are illustrated in Figure 3 in the next section, and are presented in more detail in Annex B.

### 2.2.3. Proportion of mitigatable fatalities/injuries

In order to evaluate the overall effectiveness of C-ITS in avoiding fatalities and serious injuries, the proportions of such events which cannot be addressed or mitigated by the C-ITS technologies must be considered. As already mentioned, single vehicle collisions have been removed from baseline accident rates as these cannot be avoided through device-to-device C-ITS communications technologies.

We have assumed that all types of multi-road-user accidents can be addressed through device-to-device C-ITS communications technologies, except those which involve pedestrians, riders or drivers who are under the influence of drugs or alcohol. This means that 78% of vehicle/pedestrian accidents and 82% of vehicle/vehicle and vehicle/motorcycle accidents can be addressed through the deployment of C-ITS for direct device-to-device communications[6].

### 2.2.4. Alert delivery reliability

Alert delivery reliability (also known as packet reception ratio) is the likelihood that a C-ITS warning message transmitted from one road user will be successfully received by the other intended road users.

The methodology used in this report for calculating the alert delivery reliabilities for different speeds, road types, transport modes and accident types is described in Annex C. See .

Table 19 in Annex C for an overview of the scenarios examined.

Specifically, we have reused the system-level evaluation methodology adopted by 3GPP [14] to evaluate both LTE-V2X and 802.11p. The 802.11p parameters and assumptions used in the modelling of its performance have been derived from studies performed by the NGMN [15]. We have also extended the evaluation methodology to cover rural scenarios, as well as vehicle-to-pedestrian/cyclist communications (for rural and motorway scenarios).

Alert delivery reliabilities for V2V, V2M, and V2P communications via LTE-V2X (PC5) and 802.11p have been computed for urban, rural and motorway evaluation scenarios as a function of the speed of the

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[6] SWOV, "Study on Serious Road Traffic Injuries in the EU," 2015.

road users, whilst also taking account of whether the transmission is occurring at a road junction or not. These are shown in Figure 34 to Figure 45 in Annex C, and are derived from families of curves of delivery reliability vs. transmitter-receiver distance (Figure 22 to Figure 33, Annex C), in conjunction with the AASHTO model for stopping distance.

A number of accident scenarios are then modelled for urban/rural/motorway road types, according to whether the potential accident takes place at a junction or elsewhere, and for different modes of transport involved in the potential accident (vehicle/vehicle, vehicle/motorcycle, vehicle/cyclist, and vehicle/pedestrian).

For each accident scenario, the range of assumed road user speeds (Table 22, Annex C) maps to a corresponding range of alert delivery reliability rates. The *average* reliability rate over this range is then calculated for each of LTE-V2X (PC5) and 802.11p, and used as the alert delivery reliability associated with the two technologies in the said accident scenario. The resulting alert delivery reliabilities used in the modelling can be found in Table 23 and Table 24 in Annex C.

### 2.2.5. Effectiveness of received warning messages

The effectiveness of warning messages on driver behaviour has been examined in the DRIVE C2X study [16] 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 between 65% to 68%, while a higher effectiveness of between 72% to 85% has been noted for accidents which occur elsewhere (i.e., not at junctions). Table 25 in Annex D shows the values used for the purpose of this report.

# 3 Modelling results

Figure 3 shows the modelled penetration rates of LTE-V2X (PC5) and 802.11p among vehicles, motorcycles and VRUs for the high and low scenarios.

As described earlier, the same penetration rates in vehicles is assumed for LTE-V2X (PC5) and 802.11p in the high scenario, representing a case of aggressive deployment from 2019. It can be seen that even in this optimistic case, it can take almost two decades to achieve peak penetration. The slowing growth of the penetration in vehicles visible in the later years is a result of a lifetime of 14 years assumed for all vehicles and the consequent removal from the fleet of vehicles equipped in early deployment years.

The penetration rates in vehicles in the low scenario are derived based on data from publicly available sources, and indicate a more rapid penetration growth for LTE-V2X (PC5) compared to 802.11p, with the former piggy backing on the deployment of LTE modems in cars for purposes of embedded and hybrid telematics. Peak penetrations are expected to be achieved sometime after 2040.

As explained in Section 2.2.2, penetration in motorcycles is expected to lag well behind penetration in vehicles.

The penetration of LTE-V2X (PC5) in smartphones, as assumed in the high scenario, is shown to grow particularly rapidly despite the fact that deployment is assumed to start only from 2020 (as opposed to 2019 for deployment in vehicles). This is primarily due to the short lifetime and therefore rapid 'fleet' turnover of smartphones.

A zero penetration of C-ITS technologies in smartphones is considered in the low scenario. Note that while there is considerable expectation that LTE-V2X (PC5) functionality will be incorporated into smartphones, this is by no means certain. Furthermore, inclusion of 802.11p in smartphones is considered unlikely. It is for these reasons that the low scenario is constructed to assume zero penetration of C-ITS technologies in smartphones.

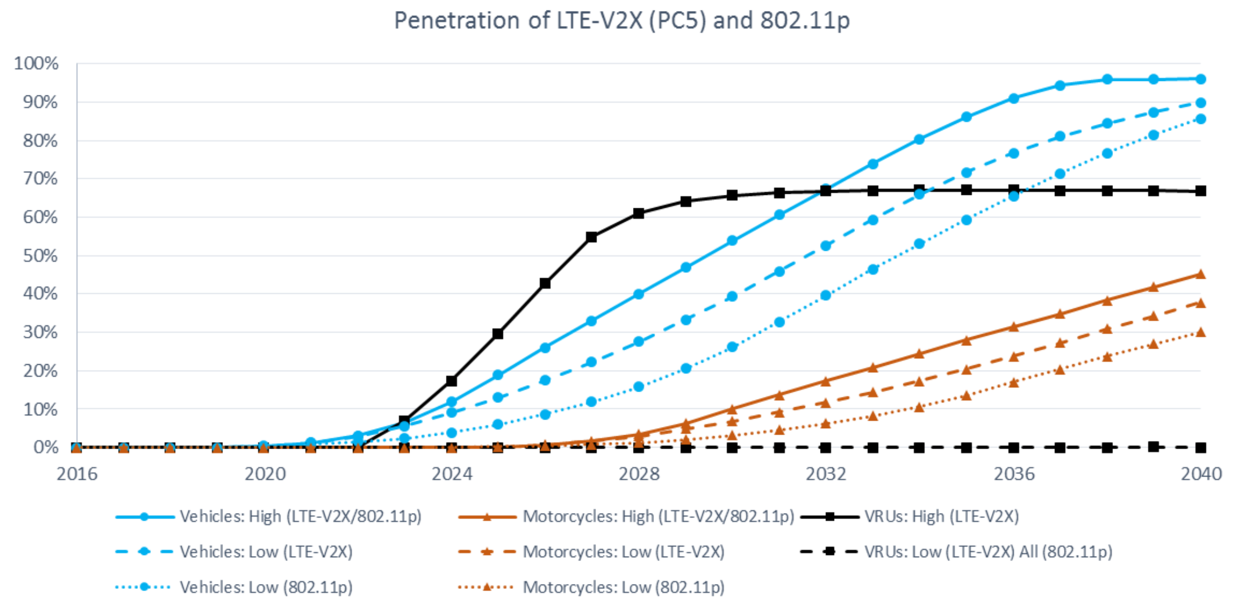

*Figure 3: Modelled penetration rates among the total populations of vehicles, motorcycles and VRUs (smartphones) for LTE-V2X (PC5) and 802.11p. High and low scenarios are depicted.*

Table 2 shows the modelled alert delivery rates of LTE-V2X (PC5) and 802.11p among vehicles, motorcycles and VRUs for the high and low scenarios. It can be seen that LTE-V2X (PC5) performs better in all cases, due to its ability to better cope in dense urban settings with a large number of competing vehicles.  In addition, LTE-V2X (PC5) it is also expected to reach higher delivery rates with high speeds in motorway/rural road environments.

*Table 2: Estimated alert delivery rates (probabilities of successful packet delivery) for LTE-V2X (PC5) and 802.11p.*

| LTE-V2X (PC5) {802.11p} | At junction | | | Not at junction | | |
|---|---|---|---|---|---|---|
| Vehicle to | Urban | Rural | Motorway | Urban | Rural | Motorway |
| Pedestrian or bicycle | 96 %<br>{78%} | 67%<br>{59%} | N/A | 88%<br>{75%} | 98%<br>{97%} | 97%<br>{63%} |
| Vehicle or motorcycle | 96%<br>{78%} | 83%<br>{66%} | N/A | 96%<br>{81%} | 99%<br>{98%} | 94%<br>{86%} |

Figure 4 and Figure 5 show estimates of the percentage of fatalities and serious injuries which can be avoided on Europe’s roads for each year up to 2040. These are derived based on the modelled penetration rates and alert delivery reliabilities described above. Note that the effectiveness of both LTE-V2X (PC5) and 802.11p remains low in the first few years of deployment. This is due to the low penetration rates of the technologies after initial deployment, which, due to relatively slow fleet turnover rates, only begin to pick up pace in the mid-2020s. This, combined with the fact that the probability of avoiding accidents using C-ITS is proportional to the square of the probability of having the technology installed, explains the slow initial ramp-up in effectiveness. These findings are in line with general observations on the effectiveness of C-ITS technologies: a distinctive feature of C-ITS is that the benefits achieved are far higher when the rate of penetration is high (sometimes referred to as the ‘network effect’).

Comparing the impacts of the two technologies on the number of accidents, it can be seen that LTE-V2X (PC5) is expected to result in a higher percentage of avoided fatalities in the future than 802.11p, with 35% vs. 24% in 2035 in the high scenario and 17% vs. 11% in the low scenario. Comparing the impact on fatalities versus serious injuries, both technologies show slightly higher benefits (in percentage points) in the case of fatalities, as the latter occur mainly in rural and motorway road types which do not involve junctions, and where the alert delivery rate is higher. For both technologies in the high scenario, the percentage of accidents avoided plateaus between 2037 and 2040 due to the technologies approaching peak penetration at that point.

Figure 6 and Figure 7 show estimates of the *cumulative* numbers of avoided fatalities and serious injuries on Europe’s roads up to the year 2040. The results indicate that the values are significant for both technologies, but with LTE-V2X (PC5) being more effective due to its superior radio link performance in all cases. The advantage of LTE-V2X (PC5) over 802.11p in the low scenario is also attributed to its higher projected penetration in vehicles. The advantage of LTE-V2X (PC5) over 802.11p is particularly significant in the high case, where LTE-V2X (PC5) penetration in smartphones allows for protection of VRUs (pedestrians and bicycles). Detailed breakdowns of the above figures by road user type can be found in Figure 46 to Figure 53 and Table 26 to Table 29 in Annex E.

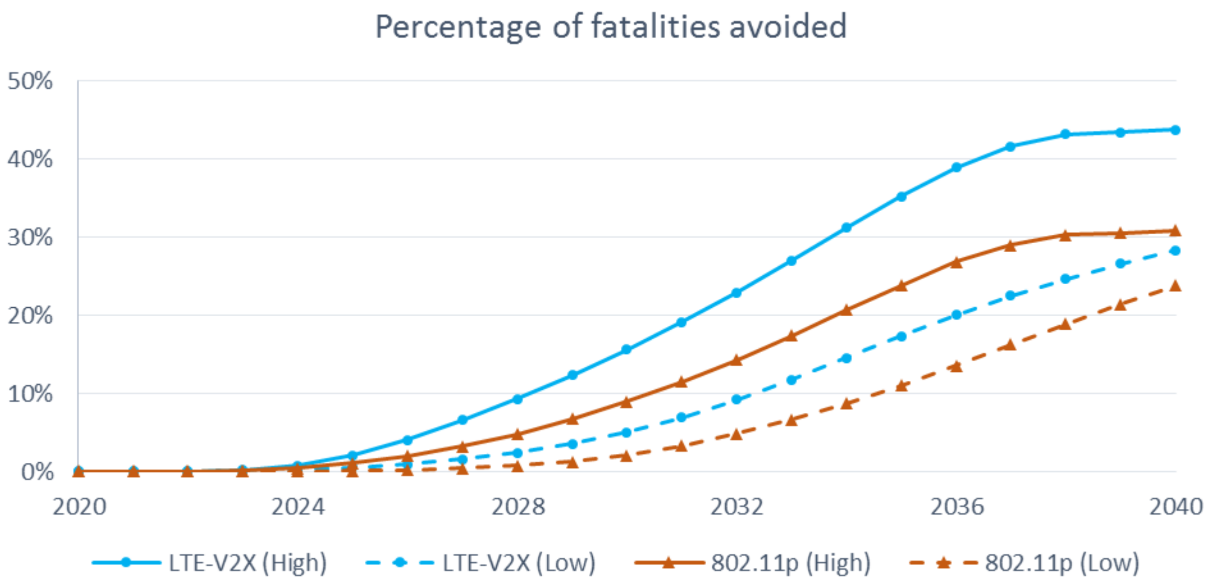

*Figure 4: Estimated percentage of fatalities avoided by LTE-V2X and 802.11p. High and low scenarios are depicted.*

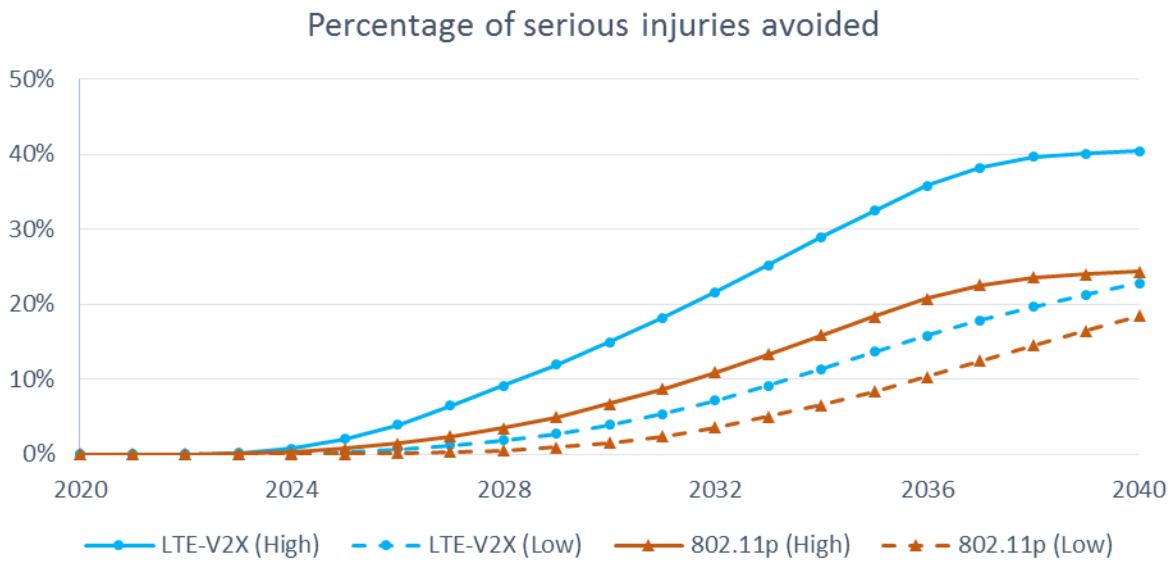

*Figure 5: Estimated percentage of serious injuries avoided by LTE-V2X (PC5) and 802.11p. High and low scenarios are depicted.*

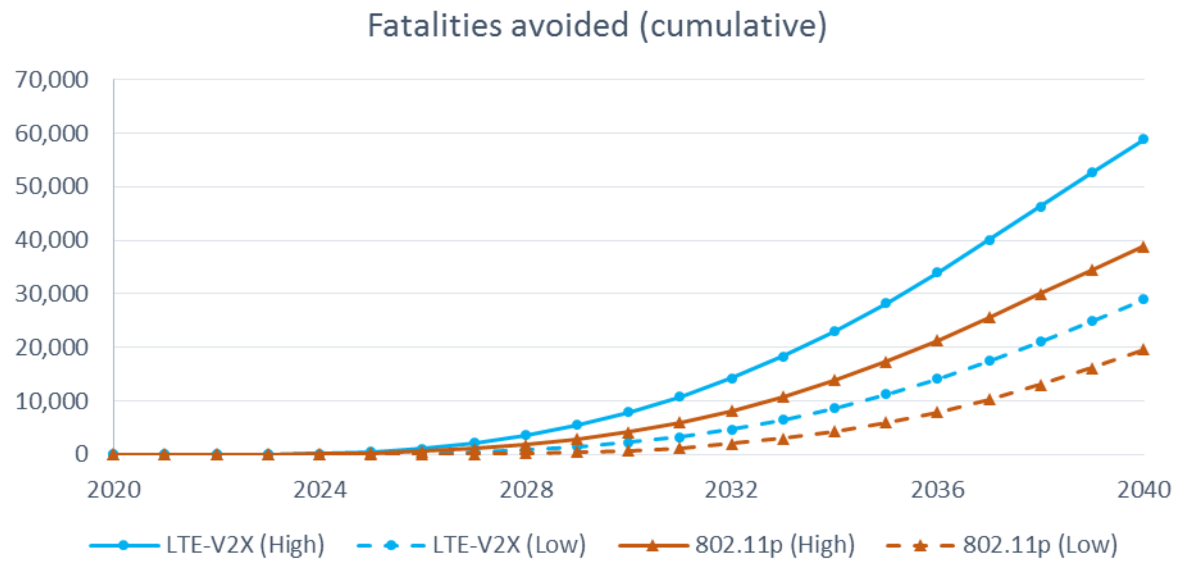

*Figure 6: Estimated cumulative numbers of fatalities avoided by LTE-V2X (PC5) and 802.11p. High and low scenarios are depicted.*

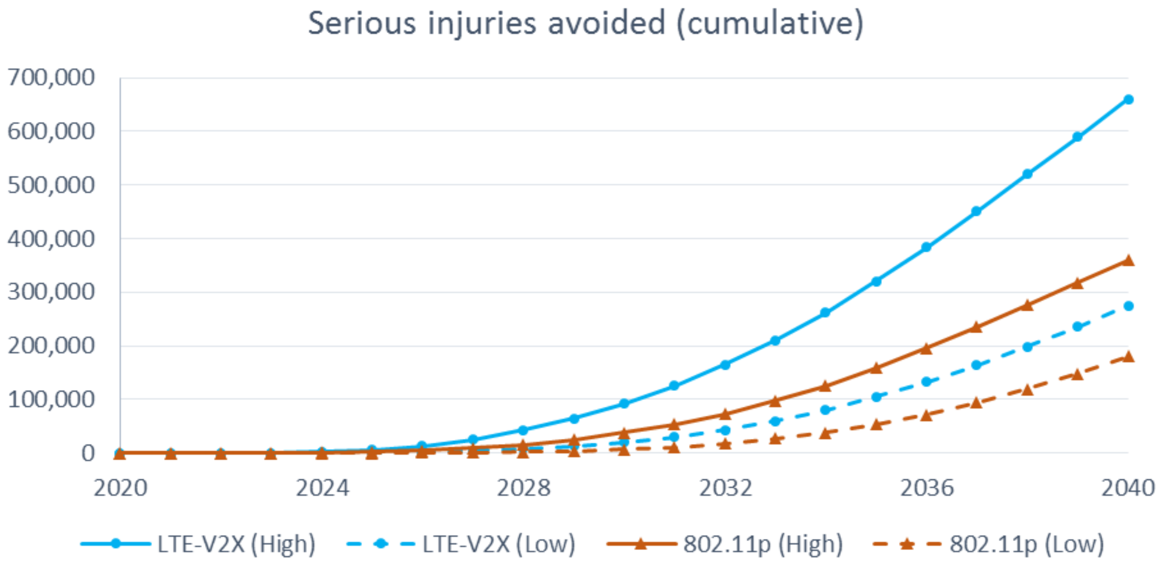

*Figure 7: Estimated cumulative numbers of serious injuries avoided by LTE-V2X (PC5) and 802.11p. High and low scenarios are depicted.*

Table 3 shows a summary of the results. Overall, the cumulative difference in impact between LTE-V2X (PC5) and 802.11p is an *additional* 9,000 lives saved and 95,000 serious injuries avoided for LTE-V2X (PC5) by 2040 compared to 802.11p in the low scenario, and an *additional* 20,000 lives saved and 300,000 serious injuries avoided in the high scenario.

Using the accidents costs from the Handbook on External Costs of Transport [17], costs of €1,870,000 and €243,100 may be associated with a fatality and a serious injury, respectively. Accordingly, the avoided societal costs achieved by deploying LTE-V2X (PC5) over 802.11p are €61 billion by 2040 in the high scenario and €22 billion in the low scenario.[7]

*Table 3: Cumulative numbers of fatalities and serious injuries avoided from 2018 to 2040.*

| LTE-V2X (PC5)<br>2018 – 2040 | Fatalities total | | Serious injuries total | |
|---|---|---|---|---|
| | High | Low | High | Low |
| Pedestrians | 12,700 | N/A | 164,828 | N/A |
| Bicycles | 5,014 | N/A | 102,159 | N/A |
| Motorcycles | 3,854 | 2,567 | 59,477 | 39,611 |
| Vehicles | 37,353 | 26,403 | 333,449 | 235,704 |
| Total | **58,921** | **28,970** | **659,913** | **275,315** |

| 802.11p<br>2018 – 2040 | Fatalities total | | Serious injuries total | |
|---|---|---|---|---|
| | High | Low | High | Low |
| Pedestrians | N/A | N/A | N/A | N/A |
| Bicycles | N/A | N/A | N/A | N/A |
| Motorcycles | 3,569 | 1,504 | 53,462 | 22,534 |
| Vehicles | 35,318 | 18,105 | 307,013 | 157,385 |
| Total | **38,887** | **19,609** | **360,474** | **179,918** |

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[7] The Handbook cost data is given in 2010€. The 2014 Net Present Value is calculated using a 4% discount rate.

# 4 Conclusions

The performance of LTE-V2X (PC5) and 802.11p direct communication C-ITS technologies was assessed and compared in the context of the reliable delivery of life-critical alerts to avoid collisions and thus save lives. Specifically, two independent counter-factual scenarios were compared: one where LTE-V2X (PC5) is the only deployed C-ITS communications technology, and another where 802.11p is the only deployed C-ITS communication technology.

Accident statistics released by the European Commission were examined, which show that high-speed rural roads/motorways, and roads in urban areas, are the most critical settings in terms of the number of vehicle accident fatalities. These accident figures were then further disaggregated by road type, by mode of transport, and by type of accident (at junction/not at junction) as baselines in different modelling scenarios.

High and low scenarios were developed for the penetration of LTE-V2X (PC5) and 802.11p in vehicles, motorcycles, and in smartphones over time. The high scenario was developed to model the case of aggressive deployments of LTE-V2X (PC5) and 802.11p in vehicles. Deployment of LTE-V2X (PC5) in smartphones was also considered in this scenario. The low scenario was developed based on data from publicly available sources and represents a less optimistic case with less rapid growth of penetration in vehicles, and no C-ITS penetration in smartphones.

Next, the radio link performance of LTE-V2X (PC5) and 802.11p were compared by modelling the alert delivery reliabilities of the two technologies for a range of road types and road user types. The modelling indicates that LTE-V2X (PC5) has a superior radio performance, particularly in dense urban settings with large numbers of competing vehicles, and in high speed roads.

The superior reliability of LTE-V2X (PC5) results in a higher number of avoided fatalities and serious injuries compared to 802.11p, with the largest differences occurring in the high scenario where LTE-V2X (PC5) can help protect pedestrians and cyclists in light of its penetration in smartphones.

By year 2040 the differences amount to

a) 9,000 more fatalities avoided by LTE-V2X (PC5) in the low scenario and 20,000 more fatalities avoided by LTE-V2X (PC5) in the high scenario, and

b) 95,000 more serious injuries avoided by LTE-V2X (PC5) in the low scenario and 300,000 more serious injuries avoided by LTE-V2X (PC5) in the high scenario,

as compared to 802.11p.

When expressed in terms of external costs avoided, this amounts to total avoided costs of €61 billion and €22 billion for LTE-V2X (PC5) compared to 802.11p in the high and low scenarios, respectively.

We identify the following conclusions and recommendations from the results of this report:

- The study indicates that LTE-V2X (PC5) outperforms 802.11p in reducing fatalities and serious injuries on the EU's roads. This is due to a combination of the superior performance of LTE-V2X (PC5) at the radio link level for *ad hoc*/direct communications between road users, and the market led conditions which better favour the deployment of LTE-V2X in vehicles and in smartphones, and include a clear evolutionary path towards 5G-V2X. **For these reasons, it is essential that EU regulations remain technology neutral and do not hinder the deployment of LTE-V2X (PC5) in favour of 802.11p for the provision of direct communications among vehicles and between vehicles and vulnerable road users.**
- An absence of interoperability at radio link level between LTE-V2X (PC5) and 802.11p is unlikely to present a substantive barrier to the reduction of road accidents in the EU in the short to medium term. The relatively low penetration of C-ITS technologies in vehicles in the first half of

the next decade (and perhaps even later) means that a vehicle equipped with LTE-V2X (PC5) or 802.11p is far more likely to collide with a vehicle that is not equipped with C-ITS technologies at all – indeed it is not until the middle of the next decade that penetration rates are expected to reach a level which results in significant impacts on accident rates. **Any regulations which mandate LTE-V2X (PC5) to be backward interoperable with 802.11p will therefore have only a limited effect in the early years of deployment pre-2025. Such regulations will run the risk of unnecessarily distorting the market in favour of 802.11p, thereby obstructing the adoption of LTE-V2X (PC5) and resulting in greater road fatalities and injuries in the longer term.**

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# Annex A – Baselines for fatalities and serious injuries

This annex presents the baselines for the number of fatalities and serious injuries disaggregated by road type and the mode of transport.

## A1. Baselines for fatalities/serious injuries over time

The annual number of fatalities in Europe has been extracted from the Eurostat (CARE) database [3]. Data is available for the period 2006 to 2015 and numbers for fatalities are provided for motorways, rural and urban roads. The overall number of fatalities has decreased over time, but the reductions have stagnated in recent years.

For our modelling to represent a "business as usual" scenario, the number of fatalities in future years are calculated using linear extrapolation based on the last two years (2014-2015) of available historic data. Historic (2012-2015) and extrapolated (2016-2040) baselines for the numbers of road traffic fatalities in the EU are presented in Table 4.

*Table 4: Baseline number of fatalities caused by road traffic accidents in the EU.*

| Year | Total |
|---|---|
| 2012 | 27,470 |
| 2013 | 25,563 |
| 2014 | 25,214 |
| 2015 | 25,075 |
| 2016 | 24,936 |
| 2018 | 24,658 |
| 2020 | 24,380 |
| 2022 | 24,102 |
| 2024 | 23,824 |
| 2026 | 23,546 |
| 2028 | 23,268 |
| 2030 | 22,990 |
| 2032 | 22,712 |
| 2034 | 22,434 |
| 2036 | 22,156 |
| 2038 | 21,878 |
| 2040 | 21,600 |

Statistics on serious injuries from road traffic accidents are not publically 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) [18]. These assumptions are used to estimate the total number of serious injuries. The same extrapolated trend for fatalities up to the year 2040 is re-used for the case of serious injuries. The baselines for the number of serious injuries are presented in Table 5.

Table 5: Baseline number of serious injuries caused by road traffic accidents in the EU.

| Year | Total |
|---|---|
| 2016 | 299,232 |
| 2018 | 295,896 |
| 2020 | 292,560 |
| 2022 | 289,224 |
| 2024 | 285,888 |
| 2026 | 282,552 |
| 2028 | 279,216 |
| 2030 | 275,880 |
| 2032 | 272,544 |
| 2034 | 269,208 |
| 2036 | 265,872 |
| 2038 | 262,536 |
| 2040 | 259,200 |

Note that the numbers presented above include single-vehicle accidents which cannot be readily avoided via C-ITS technologies for *ad hoc*/direct communications. A study from the European Transport Safety Council [4] estimates that a third of road fatalities in the EU are due to single vehicle collisions (SVCs). Accordingly, the numbers of fatalities and serious injuries in Table 4 and Table 5 have been reduced by 1/3 to obtain the baselines for the purposes of the modelling in this study.

## A2. Breakdown of fatalities/serious injuries by road type and mode of transport

The breakdowns of fatalities by the three main road types are calculated based on the Eurostat (CARE) database [3] as an average over the years 2006 to 2015. For serious injuries, data from the Drive C2X study [16] is used to derive the breakdown by road type. The resulting breakdowns by road type used for the modelling in this report are presented in Figure 8 and are fixed over time.

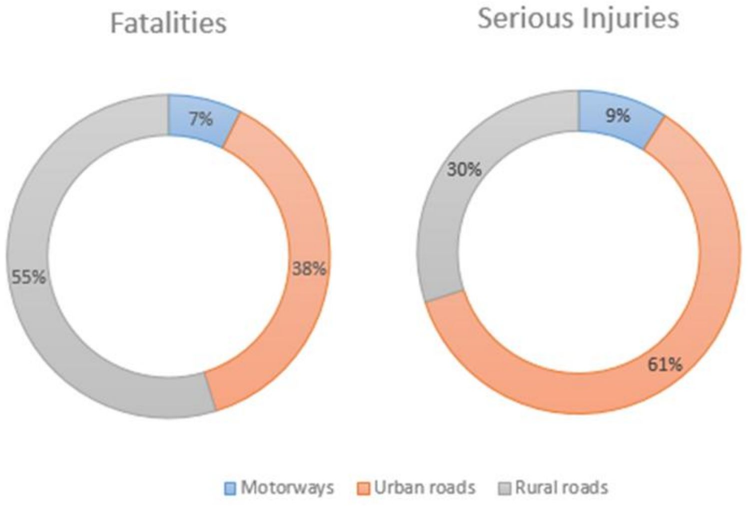

Figure 8: Breakdowns of fatalities [3] and serious injuries [16] by road type.

The numbers of fatalities and serious injuries for each road type have then been disaggregated across the different transport modes.

The breakdown of fatalities in the urban, rural and motorway scenarios by transport mode is obtained from the report “Road Safety 2015 – how is your country doing?” by the European Commission [19]. These are shown in Table 6.

*Table 6: Breakdown of fatalities by mode of transport and road type.*

| | Fatalities | | |
|---|---|---|---|
| | Urban | Rural | Motorway |
| Pedestrian | 39.0% | 11.0% | 12.0% |
| Pedal cyclist | 12.0% | 7.0% | 1.0% |
| Motor cyclist | 18.0% | 17.0% | 9.0% |
| Car occupant | 26.0% | 58.0% | 60.0% |
| Other vehicle occupant | 5.0% | 7.0% | 18.0% |

For serious injuries, the breakdown by transport mode and road type is obtained from a UK dataset published by the Department of Transport (DfT) [20] as equivalent pan-EU data is not readily available. This data has been compared to the values for the EU breakdown by transport mode (but not by road type) provided in the EuroSafe report “Injuries in the European Union – Summary of injury statistics for the years 2010-2012” [21].

The breakdown of injuries by transport mode in the UK is comparable to the equivalent pan-EU data, and consequently the UK values for the breakdowns of serious injuries by transport mode and road type are used as a proxy for the corresponding EU values. These are shown in Table 7.

*Table 7: Breakdown of serious injuries by mode of transport and road type.*

| | Serious Injuries | | |
|---|---|---|---|
| | Urban | Rural | Motorway |
| Pedestrian | 35.0% | 7.4% | 1.8% |
| Pedal cyclist | 18.7% | 10.5% | 0.0% |
| Motor cyclist | 21.7% | 25.0% | 12.5% |
| Car occupant | 21.3% | 51.6% | 70.7% |
| Bus occupant | 1.6% | 0.7% | 1.2% |
| Van occupant | 0.7% | 2.8% | 5.6% |
| HGV occupant | 0.2% | 0.9% | 7.3% |
| Other vehicle occupant | 0.8% | 1.2% | 0.8% |

## A3. Breakdown of fatalities/serious injuries by accident type

As the majority of accidents occur on *straight* sections of roads (i.e., not at junctions), a further breakdown by type of accident is applied to better model the impacts of C-ITS technology. The percentages of fatalities that occur due to accidents at road junctions is available in the report "Junctions – Traffic Safety Basic Facts 2016" published by the European Road Safety Observatory [22] and are shown in Table 8. The same breakdown has been applied to serious injuries.

*Table 8: Percentage of fatalities and serious injuries at junctions.*

| | All Roads | Motorways | Urban roads | Rural roads |
|---|---|---|---|---|
| At junction | 21% | 4% | 23% | 12% |
| Not at Junction | 79% | 96% | 77% | 88% |

# Annex B: C-ITS technology penetrations

This annex presents a derivation of the rates of penetration of LTE-V2X (PC5) and 802.11p technologies among vehicles, motorcycles and VRUs up to the year 2040. As described in the main body of this document, the two technologies are considered independently and in isolation; i.e., where only LTE-V2X (PC5) *or* only 802.11p is deployed.

The penetration rates that are derived in this annex are required to calculate the probability of any two road users being equipped with the same C-ITS technology, and in turn, the probability of avoiding a collision.

Specifically, the probability $Pr$ that any vehicle and any VRU which might collide are both equipped with technology "X" is given by

$$Pr = P_{RU1-X} P_{RU2-X} ,$$

where $0 \leq P_{RUn-X} \leq 1$ is the penetration rate of technology "X" among the population of road user $n$, where $n$ indicates vehicles, motorbikes, pedestrians and cyclists.

The penetration of C-ITS technologies in vehicles/motorcycles is calculated by estimating the number of new vehicles/motorcycles that are equipped by such technologies, and dividing this by the total number of vehicles/motorcycles in the entire fleet. This is described in the following sections.

A similar approach is applied in relation to technology penetration rates among VRUs, where deployment in smartphones is used as a proxy for deployments in vehicles/motorcycles.

## B1. Technology penetration in vehicles and motorcycles

The technology penetration rate in any given year can be derived by calculating the annual cumulative number of new vehicles/motorcycles equipped with technology "X" (having subtracted the number of equipped vehicles/motorcycles that have passed their maximum lifetime), and dividing this by the total number of vehicles/motorcycles on the road in that year. This is described in the following sections.

### B1.1. Numbers of new vehicles/motorcycles and the fleet sizes in the EU fleet

In this section, we quantify the annual number of new vehicle/motorcycle registrations, as well as the size of the total vehicle/motorcycle fleet on the EU roads over time.

The number of new vehicle/motorcycle registrations and the size of the total vehicle/motorcycle fleets are extracted from Eurostat [5] and are available up to the year 2015 for the following vehicle types:

a) Motorcycles and mopeds
b) Passenger cars
c) Lorries (including light goods road vehicles)
d) Motor coaches, buses and trolley buses

Categories (b) to (d) are merged together as a single "vehicles" category for the purposes of this report, whilst motorcycles and mopeds are grouped as a separate "motorcycles" category.

Projections of the vehicle/motorcycle numbers into the future up to the year 2040 are derived by extrapolating the 2015 data from Eurostat using specific annual new registration growth rates and annual total fleet growth rates. These growth rates are obtained from a separate transport sector analysis carried out by Ricardo [23] and are presented in Table 9.

The effect of older vehicles/motorcycle leaving the fleet at the end of their lifetime is also accounted for. For this purpose, a lifetime of 14 years [24] is considered for vehicles, and a lifetime of 17 years [25] is considered for motorcycles.

The resulting number of new registrations and total fleet sizes used for the purposes of this report are presented in Table 10.

*Table 9: Annual growth rates for new vehicle/motorcycle registrations and for the total fleets in the EU.*

| Year | Annual new registration growth rate | | Annual total fleet growth rate | |
|---|---|---|---|---|
| | Motorcycles | Vehicles | Motorcycles | Vehicles |
| 2016 | 1.9% | 1.8% | 1.1% | 1.0% |
| 2018 | 1.9% | 1.7% | 1.1% | 1.0% |
| 2020 | 1.8% | 1.6% | 1.0% | 1.0% |
| 2022 | 1.0% | 1.0% | 0.8% | 0.5% |
| 2024 | 0.9% | 1.0% | 0.8% | 0.5% |
| 2026 | 0.3% | 0.4% | 0.8% | 0.5% |
| 2028 | 0.3% | 0.4% | 0.8% | 0.5% |
| 2030 | 0.3% | 0.4% | 0.8% | 0.5% |
| 2032 | 0.8% | 0.8% | 0.9% | 0.7% |
| 2034 | 0.8% | 0.7% | 0.9% | 0.7% |
| 2036 | 1.1% | 0.8% | 0.9% | 0.7% |
| 2038 | 1.1% | 0.8% | 0.9% | 0.7% |
| 2040 | 1.0% | 0.8% | 0.9% | 0.6% |

*Source: Ricardo*

*Table 10: Annual numbers of new vehicles/motorcycles sold and the total vehicles/motorcycle fleet sizes in the EU.*

| Year | New sales (in millions) | | Total fleet (in millions) | |
|---|---|---|---|---|
| | Motorcycles | Vehicles | Motorcycles | Vehicles |
| 2015* | 1.26 | 19.48 | 34.42 | 289.13 |
| 2016 | 1.28 | 19.82 | 34.79 | 292.09 |
| 2018 | 1.33 | 20.50 | 35.54 | 298.01 |
| 2020 | 1.38 | 21.19 | 36.29 | 303.92 |
| 2022 | 1.41 | 21.62 | 36.86 | 306.91 |
| 2024 | 1.44 | 22.05 | 37.43 | 309.89 |
| 2026 | 1.45 | 22.36 | 38.01 | 312.82 |
| 2028 | 1.46 | 22.55 | 38.60 | 315.70 |
| 2030 | 1.47 | 22.75 | 39.19 | 318.58 |
| 2032 | 1.50 | 23.09 | 39.93 | 323.18 |
| 2034 | 1.52 | 23.44 | 40.67 | 327.79 |
| 2036 | 1.55 | 23.80 | 41.41 | 332.30 |
| 2038 | 1.58 | 24.17 | 42.15 | 336.70 |
| 2040 | 1.62 | 24.55 | 42.88 | 341.10 |

**Source: Eurostat*

## B1.2. Penetration of 802.11p in new vehicles and motorcycles

We have developed two scenarios to account for prediction uncertainties:

- **"Low" scenario –** Based on data from Visiongain [9] which describes the future penetration rates of 802.11p in vehicles.
- **"High" scenario –** Assuming a rapid growth of 802.11p penetration in new vehicles from 2019.

The projected future penetration rates for 802.11p in new vehicles and motorcycles for these two scenarios are calculated as described next.

### B1.2.1. Low scenario – 802.11p

***Vehicles***

Current and projected future penetration rates for 802.11p in new cars entering the EU fleet have been analysed based on data obtained from Visiongain [9].

To adjust for the situation in the EU (with C-ITS technology only expected to be deployed from 2019) the timeline from the Visiongain report[8] has been moved back by 4 years. Values up to year 2040 have been derived based on polynomial extrapolation of the Visiongain data.

***Motorcycles***

The same penetration rates as for vehicles are used for motorcycles but delayed by an additional 5 years to account for the fact that motorcycle solutions are at an earlier stage of development.[9]

### B1.2.2. High scenario – 802.11p

***Vehicles***

This scenario assumes a very rapid growth rate in new vehicles starting from 2019.

Over the subsequent 6 year period, most vehicle models will go through a refresh cycle, so it can be expected that all new vehicles would be equipped by 2025 in an aggressive deployment scenario. Thus the penetration in new cars would be 25% in 2022 (3 years after start of deployments – providing a slow initial ramp rate[10]), 50% in 2023, 75% in 2024, and 100% in 2025.

***Motorcycles***

The same penetration rates as for vehicles are used for motorcycles but delayed by 5 years to account for the fact that motorcycle solutions are at an earlier stage of development.

Figure 9 shows the 802.11p penetration rates in the high and low scenarios, for both vehicles and motorcycles. Note again that these refer to penetration in *new* vehicles and further calculations are required to derive the penetration across the entire fleets, as described later.

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[8] Global penetration rates from this source are not representative of the European situation, as this technology has not been deployed in Europe yet. To date, there are no known commercially-available vehicles with this technology built-in, although it is known that some OEMs plan to launch models equipped with this technology in the US. It is expected that this technology may start to become available in the EU from 2019.

[9] A V2M solution was showcased by Honda in 2014 but this type of V2V is still in early product development. Other technologies such as ABS and dipped beam headlights were deployed in motorcycles with 11 and 2 year delays with respect to vehicles respectively, so it is assumed that a 5 year delay might be appropriate in this case.

[10] The penetration in the first three years is lower bounded by the penetration that is assumed in the low scenario.

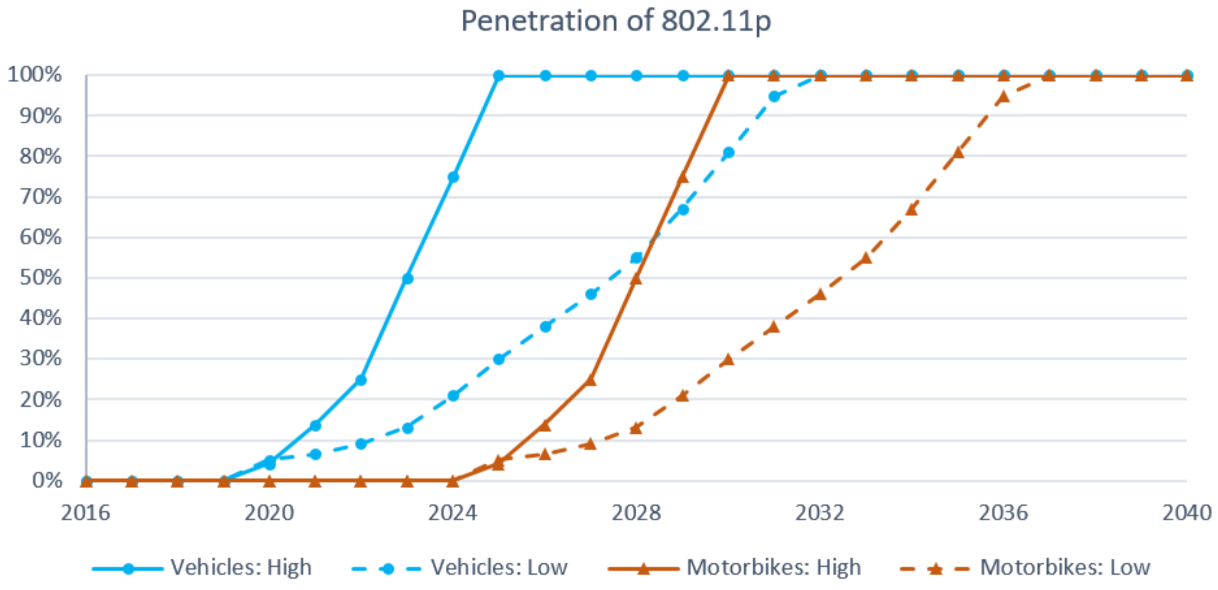

*Figure 9: Penetration rates of 802.11p in **new** vehicles and motorcycles in high and low scenarios.*
*Note: The high scenario for vehicles represents rapid growth in new vehicles from 2019. The low scenario for vehicles is developed based on data from Visiongain. The values for motorcycles correspond to a 5 year relative delay.*

## B1.3. Penetration of LTE-V2X (PC5) in new vehicles and motorcycles

Again, we have developed two scenarios to account for prediction uncertainties:

- **“Low” scenario –** Based on data from IHS [11] [12].
- **“High” scenario –** Assuming a rapid growth in LTE-V2X (PC5) penetration in new vehicles from 2019 (analogous to the approach we adopted for 802.11p).

The projected future penetration rates for LTE-V2X (PC5) in new vehicles and motorcycles for these two scenarios are calculated as described next.

### B1.3.1. Low scenario – LTE-V2X (PC5)

***Vehicles:***

a) The basis for the calculation of the technology penetration rates are the percentages of new vehicles with embedded telematics and hybrid telematics. These are obtained from a US dataset produced by IHS Markit [11]. These are then multiplied by the percentages of embedded telematics that are delivered via LTE, as obtained from a European dataset produced by IHS Automotive [12]. These products represent the penetration of LTE in new vehicles and are shown in Table 11. Note that these figures relate to LTE only, and not LTE-V2X (PC5). Figure 10 shows the corresponding values when linearly extrapolated out to year 2040.

b) To account for the availability of LTE-V2X (PC5) in new vehicles, we consider the penetration of 3GPP Release 14[11] features in LTE chips. It is assumed that LTE chipsets equipped with 3GPP

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[11] This is the first release of the LTE standard developed by the 3GPP which includes LTE-V2X capabilities.

Release 14 technical specifications will begin to hit the market in 2018, as indicated by at least one chip-vendor [13], and that full penetration in all LTE-equipped devices is achieved six years later assuming a linear growth (see Table 12).

c) Finally, to calculate the penetration of LTE-V2X (PC5) in vehicles, the penetration of LTE in vehicles – calculated under (a) – is multiplied with the penetration of LTE-V2X (PC5) in LTE chips – calculated under (b). These are illustrated in Figure 10.

***Motorcycles:***

In line with the assumptions described for 802.11p, a five-year delay in the penetration timeline for LTE-V2X (PC5) is applied.

### B1.3.2. High scenario – LTE-V2X (PC5)

We adopt the same penetration rates in new vehicles as used for the 802.11p high scenario. This provides an opportunity to compare LTE-V2X (PC5) and 802.11p based on their technical performance, rather than any differential penetration rates.

Figure 11 shows the LTE-V2X (PC5) penetration rates in the high and low scenarios, for both vehicles and motorcycles. Note again that these refer to penetration in *new* vehicles and further calculations are required to derive the penetration across the total fleets, as described next.

*Table 11: Penetration rates of LTE (not LTE-V2X PC5) in* ***new*** *vehicles as derived from literature.*

| | Feature level take rate of embedded + hybrid telematics [11] | LTE share in embedded telematics sales [12] | LTE share in new vehicle sales |
|---|---|---|---|
| 2014 | 36% | 0% | 0.00% |
| 2015 | 43% | 1% | 0.43% |
| 2016 | 50% | - | |
| 2017 | 56% | 9% | 5.04% |
| 2018 | 61% | - | - |
| 2019 | 66% | 27% | 17.82% |
| 2020 | 70% | - | - |

*Table 12: Penetration rates of LTE-V2X (PC5) in* ***new*** *LTE chips.*

| Penetration rates of LTE-V2X (PC5) in LTE chips | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|---|---|---|
| | 0% | 17% | 33% | 50% | 67% | 83% | 100% |

## B1.4. Penetration across the entire fleet

The objective is to estimate the penetrations of the two C-ITS technologies across the entire EU fleet.

To this end, the annual technology penetration rates $P_{New}(t)$ in new vehicles/motorcycles (Figure 9 and Figure 11) are multiplied with the annual numbers $M_{New}(t)$ of new vehicles/motorcycles (Table 10). The products $N_{New}(t) = M_{New}(t)P_{New}(t)$ provide estimates of the number of new vehicles/motorbikes equipped with C-ITS technology in any given year.

The penetration rates $P(t)$ across the entire fleet are then calculated by dividing the cumulative number $L_{New}(t)$ of new vehicles/motorcycles equipped with C-ITS technology (having subtracted the number $N_{Scrap}(t)$ of equipped vehicles that have passed their maximum lifetime) by the total number $N(t)$ of vehicles/motorbikes in the fleet (Table 10); i.e.,

$$P(t) = \frac{L_{New}(t)}{N(t)} = \frac{1}{N(t)} \sum_{i \leq t} \{N_{New}(t) - N_{Scrap}(t)\}$$

Figure 12 and Figure 13 illustrate the penetration rates of the two technologies across the entire fleet for the high and low scenarios.

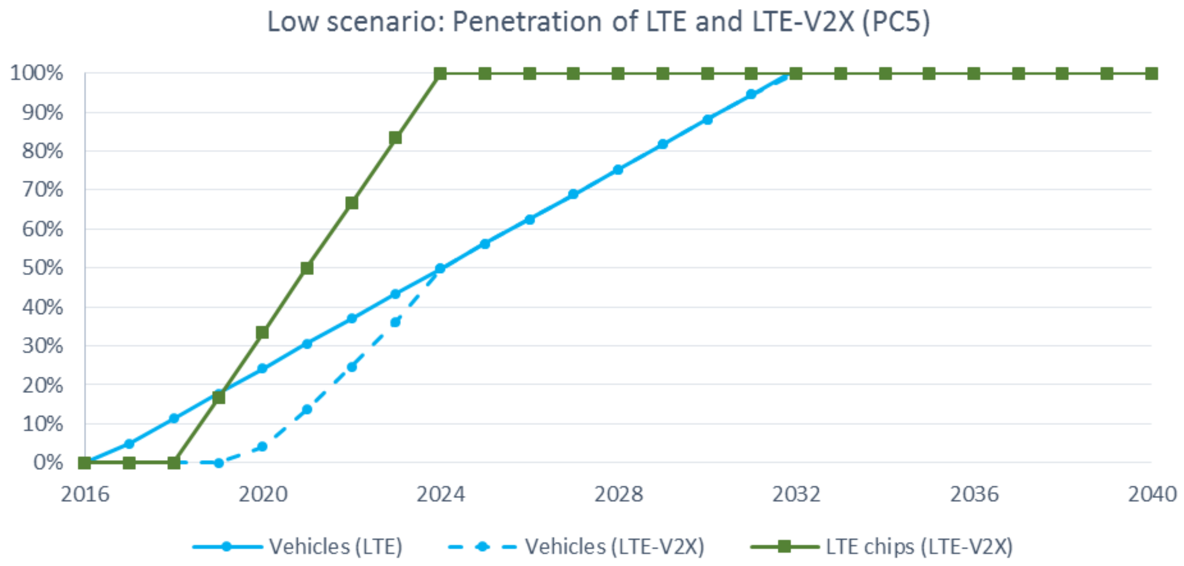

*Figure 10: Low scenario penetration rates of LTE and LTE-V2X (PC5) in **new** vehicles.*

*Note: 3GPP Release 14 (LTE-V2X PC5) penetration assumes first deployment in 2018 and full penetration in new LTE chipsets after 6 years. Also shown is the penetration of LTE in new vehicles based on IHS data and linearly extrapolated to 2040. The low scenario is obtained by multiplying these two penetrations.*

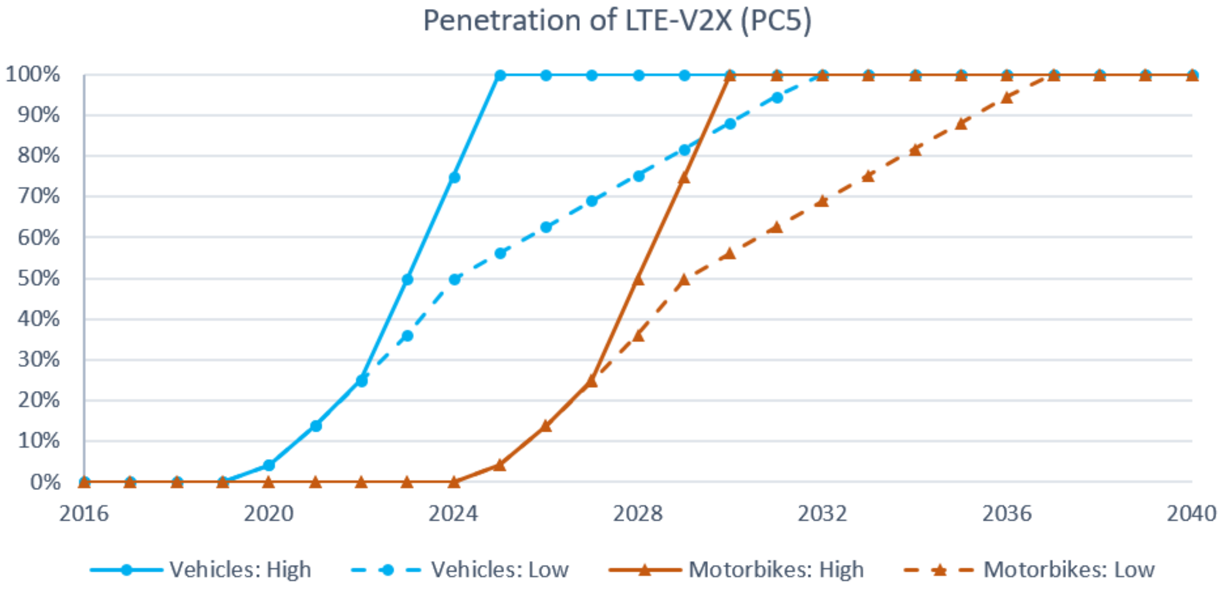

*Figure 11: Penetration rates of LTE-V2X (PC5) in **new** vehicles and motorcycles in high and low scenarios.*

*Note: The high scenario for vehicles represents rapid growth from 2019. The low scenario for vehicles is developed based on data from IHS. The values for motorcycles correspond to a 5 year delay.*

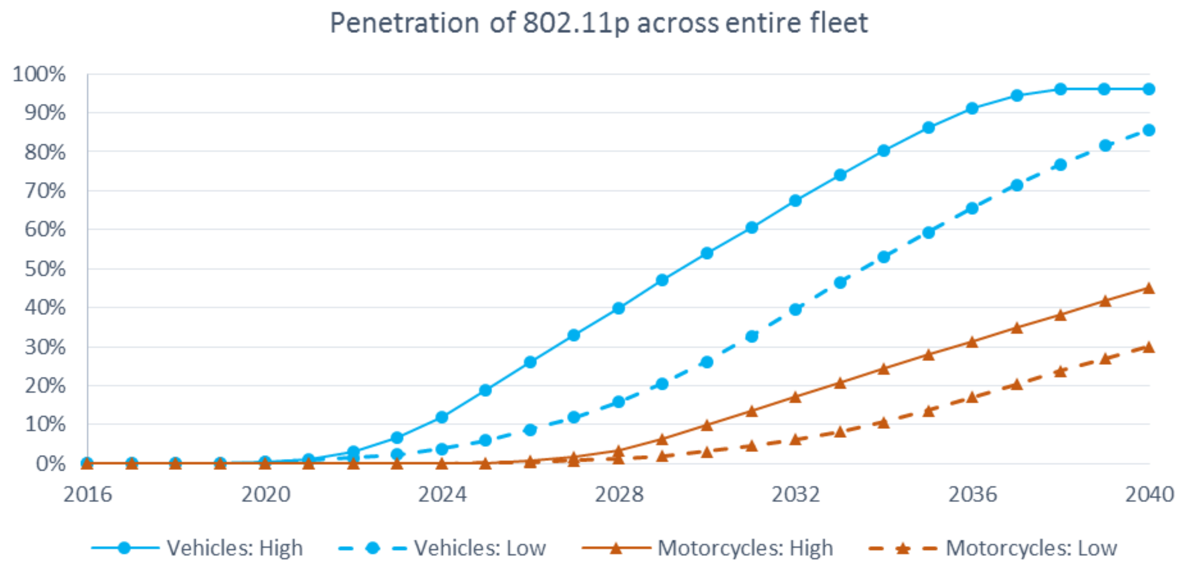

*Figure 12: Penetration rate of 802.11p across the* ***entire*** *fleet in high and low scenarios.*

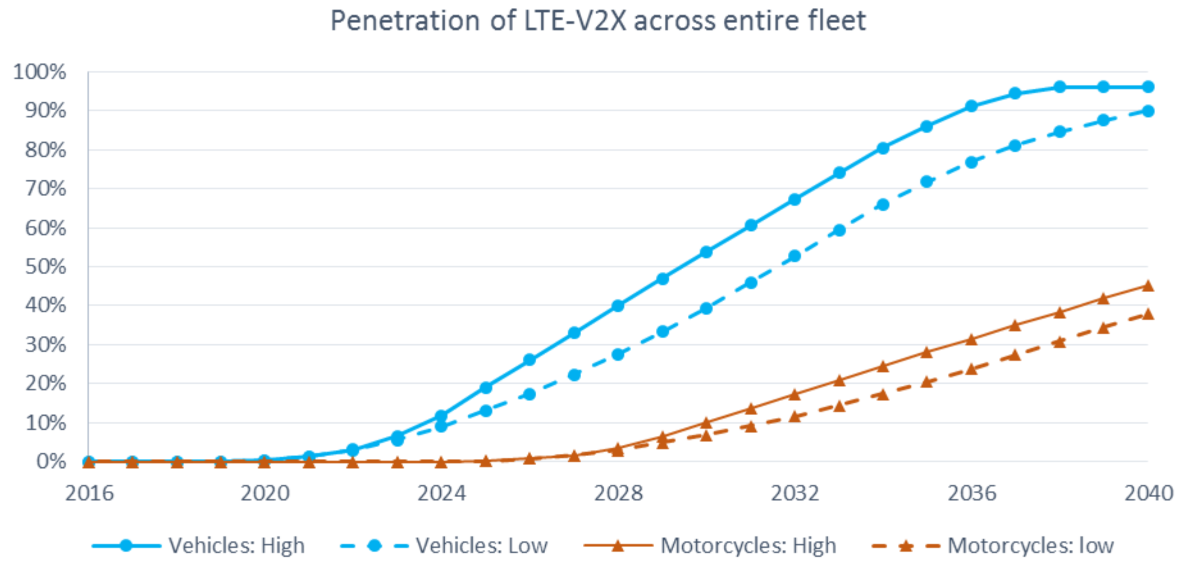

*Figure 13: Penetration rate of LTE-V2X (PC5) across the* ***entire*** *fleet in high and low scenarios.*

## B2. Technology penetration among vulnerable road users

The penetration of LTE-V2X (PC5) in smartphones is used as a proxy for the penetration of LTE-V2X (PC5) among VRUs (pedestrians or cyclists)[12].

To this end, the penetration rates of LTE-V2X (PC5) among VRUs are calculated by multiplying the penetration rates of smartphones among the population with the penetration rates of LTE-V2X (PC5) in smartphones. This is described in the following sections.

Note that the mobile equipment vendors in 5GAA do not foresee future deployments of 802.11p in smartphones. While we see the prospects of carrier aggregation between LTE-V2X (PC5) and LTE down the line, we see no market demand for a separate 802.11p chip in a smartphone, especially given the relatively higher power consumption of such technology. For this reason, a zero penetration of 802.11p in smartphones is assumed.

### B2.1. Penetration of smartphones across the EU population

Current smartphone penetration rates among the population (percentage of the population owning a smartphone) have been obtained from Statista [6] [7]. These are shown in bold in Table 13, with the non-bold figures derived through linear interpolation.

*Table 13: Penetration rates of smartphones within EU population (source: Statista).*

| | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|---|---|
| **Central + Eastern EU** | **13%** | 19% | 26% | 32% | 39% | 45% | 52% | **58%** |
| **Western Europe** | **23%** | 30% | 37% | 44% | 51% | 58% | **65%** | 72% |

The penetration rate of smartphones amongst the whole EU population is derived by extrapolating the average of Central + Eastern and Western Europe penetration rates (Table 13), whilst taking account of the maximum penetration that could be achieved based on the future age distribution from EU population projections [8].

In this context, 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 [26], with the percentage linearly increasing to 31% in 2024 and 59% in 2029. This value is then kept constant for future years.

Table 14 shows the resulting smartphone penetration rates. Note that these penetration rates must subsequently be multiplied by the penetration of LTE-V2X (PC5) in smartphones (as described later).

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[12] Note: VRUs are considered to consist of pedestrians and cyclists for the purposes of this report. Motorcycles have not been classified as VRUs but as a separate category. The distinction is that motorcycles are assumed to have a dedicated antenna for using C-ITS technologies, whereas VRUs are modelled as using C-ITS technologies via their smartphones.

Table 14: Penetration of smartphones within EU population (extrapolated).

| | 2015 | 2016 | 2017 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|---|
| Penetration rates of smartphones | 45% | 52% | 59% | 79% | 84% | 84% | 84% |

### B2.2. Penetration of LTE-V2X (PC5) in new smartphones

We have again developed high and low scenarios to model the penetration rates of LTE-V2X (PC5) in smartphones. These are described next.

**Low scenario – LTE-V2X (PC5) in smartphones**

Here we assume that there will be no deployment of LTE-V2X (PC5), or 802.11p, in smartphones.

**High scenario – LTE-V2X (PC5) in smartphones**

Here we assume that the penetration of LTE-V2X (PC5) in new smartphones will follow the same *profile* as assumed earlier for penetration of LTE-V2X (PC5) in new LTE chips (Table 12); i.e., full penetration is achieved within 6 years. We also make the following additional assumptions:

- Penetration rates in smartphones are considered to be the same for pedestrians and cyclists.
- The deployment of LTE-V2X (PC5) in smartphones is delayed until 2022 to allow for the deployment of LTE-V2X (PC5) in new vehicles to reach 25%, which is considered to trigger demand for LTE-V2X (PC5) in smartphones.
- A cap of 80% on the penetration of LTE-V2X (PC5) in smartphones is imposed, based on the rationale that 20% of users who own a smartphone will not use it for purposes of road safety, for reasons of privacy or other reasons.

Figure 14 shows the resulting penetration rates of LTE-V2X (PC5) in new smartphones for the high and low scenarios.

### B2.3. Penetration of LTE-V2X (PC5) among VRUs

The penetration rates of LTE-V2X (PC5) among VRUs are calculated by multiplying the penetration rates of LTE-V2X (PC5) in new smartphones (Figure 14) with the cumulative stock of new smartphones. The stock of new smartphones, $P_{12-80}(t)$, is calculated based on the total penetration rate of smartphones among the EU population (Table 14) in combination with a stock model for smartphones based on a 2-year lifetime [27].

To this end, the annual technology penetration rate $P_{New}(t)$ in new smartphones (Figure 14) is multiplied with the stock of new smartphones $P_{12-80}(t)$ to obtain estimates of the number of new smartphones $S_{New}(t) = P_{12-80}(t)P_{New}(t)$ that are equipped with C-ITS technology in any given year. $S_{New}(t)$ is then used to obtain the cumulative number of smartphones equipped with C-ITS technology in any given year, $K_{New}(t)$, based on a two year lifetime.

The penetration rates $P(t)$ across the entire population are then calculated by dividing the cumulative number $K_{New}(t)$ of the population owning a smartphones equipped with C-ITS technology (having subtracted the number$S_{Scrap}(t)$ of equipped smartphones that have passed their maximum lifetime) by the total number$U(t)$ of projected population [8]; i.e.,

$$P(t) = \frac{K_{New}(t)}{U(t)} = \frac{1}{U(t)} \sum_{i \le t} \{S_{New}(t) - S_{Scrap}(t)\}$$

The resulting penetration rates are shown in Figure 15, where the cap of 67% is due to the product of 80% (cap on users of LTE-V2X (PC5) on smartphones) and 84% (cap on penetration of smartphones among the population).

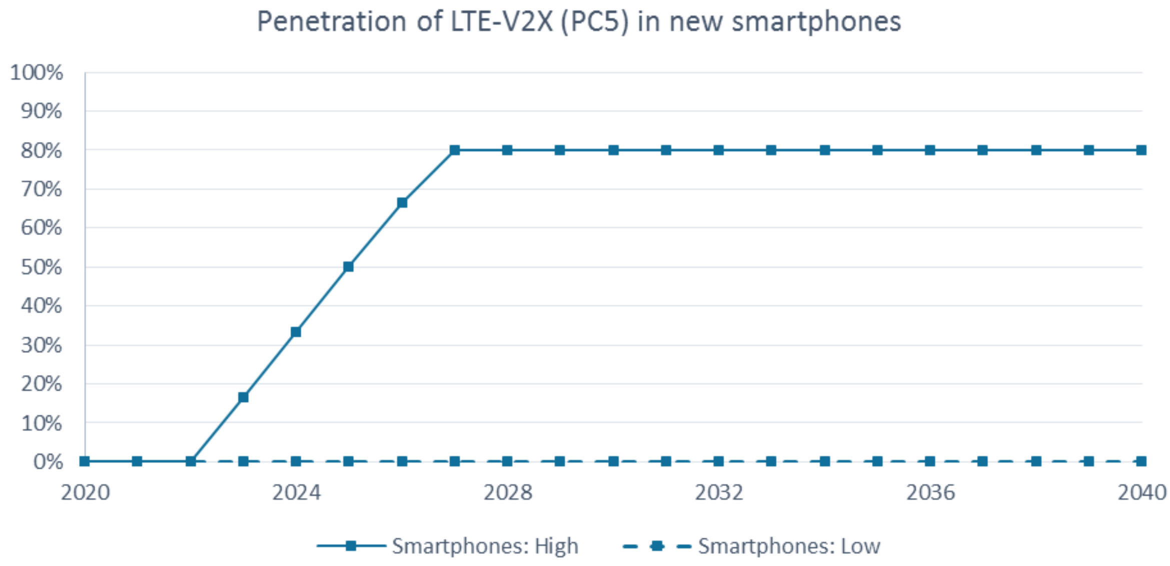

*Figure 14: Penetration rates of LTE-V2X (PC5) in **new** smartphones for high and low scenarios.*

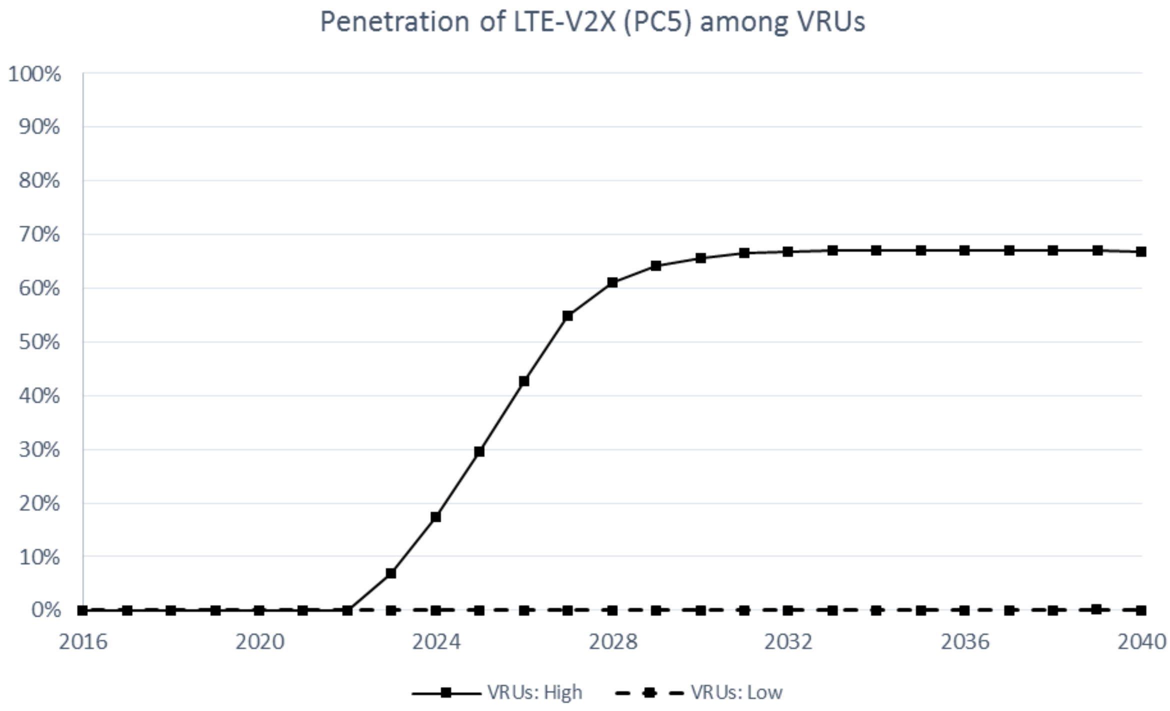

*Figure 15: Penetration rates of LTE-V2X (PC5) among vulnerable road users for high and low scenarios.*

## B3. Summary of technology penetration rates

The resultant penetration rates of LTE-V2X (PC5) and 802.11p in vehicles, motorcycles and VRUs used for the purposes of this report are presented in Table 15 and Table 16.

.

*Table 15: Penetration rates of LTE-V2X (PC5) and 802.11p – High scenario.*

| | LTE –V2X (PC5) penetration rate | | | | 802.11 penetration rate | | | |
|---|---|---|---|---|---|---|---|---|
| | **Pedestrian** | **Bicycle** | **Motorcycle** | **Vehicle** | **Pedestrian** | **Bicycle** | **Motorcycle** | **Vehicle** |
| **2018** | 0% | 0% | 0% | 0% | N/A | N/A | 0% | 0% |
| **2019** | 0% | 0% | 0% | 0% | N/A | N/A | 0% | 0% |
| **2020** | 0% | 0% | 0% | 0% | N/A | N/A | 0% | 0% |
| **2021** | 0% | 0% | 0% | 1% | N/A | N/A | 0% | 1% |
| **2022** | 0% | 0% | 0% | 3% | N/A | N/A | 0% | 3% |
| **2023** | 7% | 7% | 0% | 7% | N/A | N/A | 0% | 7% |
| **2024** | 17% | 17% | 0% | 12% | N/A | N/A | 0% | 12% |
| **2025** | 30% | 30% | 0% | 19% | N/A | N/A | 0% | 19% |
| **2026** | 43% | 43% | 1% | 26% | N/A | N/A | 1% | 26% |
| **2027** | 55% | 55% | 2% | 33% | N/A | N/A | 2% | 33% |
| **2028** | 61% | 61% | 4% | 40% | N/A | N/A | 4% | 40% |
| **2029** | 64% | 64% | 6% | 47% | N/A | N/A | 6% | 47% |
| **2030** | 66% | 66% | 10% | 54% | N/A | N/A | 10% | 54% |
| **2031** | 66% | 66% | 14% | 61% | N/A | N/A | 14% | 61% |
| **2032** | 67% | 67% | 17% | 67% | N/A | N/A | 17% | 67% |
| **2033** | 67% | 67% | 21% | 74% | N/A | N/A | 21% | 74% |
| **2034** | 67% | 67% | 24% | 80% | N/A | N/A | 24% | 80% |
| **2035** | 67% | 67% | 28% | 86% | N/A | N/A | 28% | 86% |
| **2036** | 67% | 67% | 31% | 91% | N/A | N/A | 31% | 91% |
| **2037** | 67% | 67% | 35% | 94% | N/A | N/A | 35% | 94% |
| **2038** | 67% | 67% | 38% | 96% | N/A | N/A | 38% | 96% |
| **2039** | 67% | 67% | 42% | 96% | N/A | N/A | 42% | 96% |
| **2040** | 67% | 67% | 45% | 96% | N/A | N/A | 45% | 96% |

*Table 16: Penetration rates of LTE-V2X (PC5) and 802.11p – Low scenario.*

| | LTE –V2X penetration rate | | | | 802.11 penetration rate | | | |
|---|---|---|---|---|---|---|---|---|
| | **Pedestrian** | **Bicycle** | **Motorcycle** | **Vehicle** | **Pedestrian** | **Bicycle** | **Motorcycle** | **Vehicle** |
| **2018** | N/A | N/A | 0% | 0% | N/A | N/A | 0% | 0% |
| **2019** | N/A | N/A | 0% | 0% | N/A | N/A | 0% | 0% |
| **2020** | N/A | N/A | 0% | 0% | N/A | N/A | 0% | 0% |
| **2021** | N/A | N/A | 0% | 1% | N/A | N/A | 0% | 1% |
| **2022** | N/A | N/A | 0% | 3% | N/A | N/A | 0% | 1% |
| **2023** | N/A | N/A | 0% | 6% | N/A | N/A | 0% | 2% |
| **2024** | N/A | N/A | 0% | 9% | N/A | N/A | 0% | 4% |
| **2025** | N/A | N/A | 0% | 13% | N/A | N/A | 0% | 6% |
| **2026** | N/A | N/A | 1% | 17% | N/A | N/A | 0% | 9% |
| **2027** | N/A | N/A | 2% | 22% | N/A | N/A | 1% | 12% |
| **2028** | N/A | N/A | 3% | 28% | N/A | N/A | 1% | 16% |
| **2029** | N/A | N/A | 5% | 33% | N/A | N/A | 2% | 21% |
| **2030** | N/A | N/A | 7% | 39% | N/A | N/A | 3% | 26% |
| **2031** | N/A | N/A | 9% | 46% | N/A | N/A | 5% | 33% |
| **2032** | N/A | N/A | 12% | 53% | N/A | N/A | 6% | 40% |
| **2033** | N/A | N/A | 14% | 59% | N/A | N/A | 8% | 47% |
| **2034** | N/A | N/A | 17% | 66% | N/A | N/A | 11% | 53% |
| **2035** | N/A | N/A | 20% | 72% | N/A | N/A | 14% | 59% |
| **2036** | N/A | N/A | 24% | 77% | N/A | N/A | 17% | 66% |
| **2037** | N/A | N/A | 27% | 81% | N/A | N/A | 20% | 71% |
| **2038** | N/A | N/A | 31% | 85% | N/A | N/A | 24% | 77% |
| **2039** | N/A | N/A | 34% | 87% | N/A | N/A | 27% | 82% |
| **2040** | N/A | N/A | 38% | 90% | N/A | N/A | 30% | 86% |

# Annex C: Alert delivery reliability

This annex is divided into three main sections:

- C1 System-level evaluation methodology – In this section the methodology and assumptions used in the system-level simulations of LTE-V2X (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), rural (2-lane linear model), and motorway (6-lane linear model) scenarios. We have re-used the methodology adopted by 3GPP [14] to evaluate LTE-V2X 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 [15]. We have also extended the evaluation methodology to cover rural scenarios, as well as vehicle-to-pedestrian/cyclist communications for rural and motorway scenarios.
- C2. 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.
- C3. 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-V2X (PC5) and 802.11p for a number of accident scenarios.

## C1. System-level evaluation methodology

### 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.

### Evaluation scenarios

Table 17 presents the parameters used in the evaluation of LTE-V2X (PC5).

Three cases for the *dropping* (specifying the locations) of vehicle UEs are defined: urban case, motorway 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 18 shows additional parameters used in the evaluation of 802.11p.

*Table 17: Parameters for the evaluation of LTE-V2X (PC5).*

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

*Table 18: 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 |
| CWmin | 3 |
| AIFS | 58 us,<br>AIFS = (AIFSN×Slot)+SIFS<br>where SIFS = 32 us |

### UE drop and mobility model

Figure 16, Figure 17 and Figure 18 illustrate the road configurations for the three urban, motorway, 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, motorway, and rural evaluation scenarios are shown in Table 19.

.

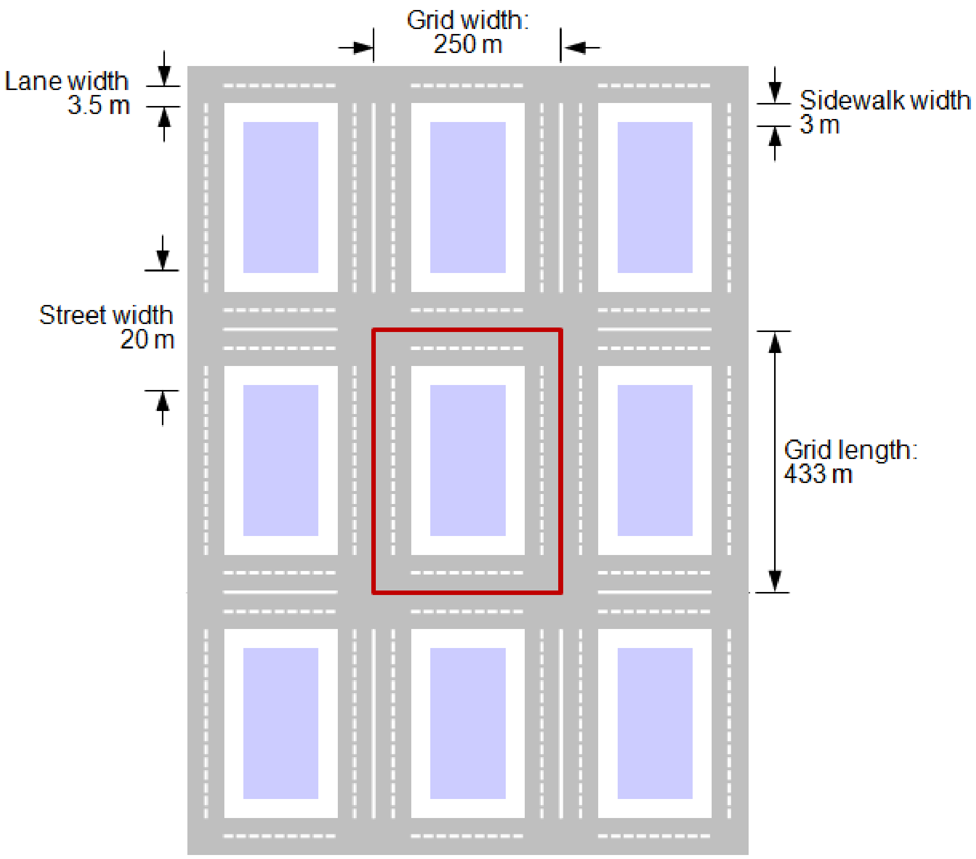

*Figure 16: Road configuration for urban evaluation scenario.*

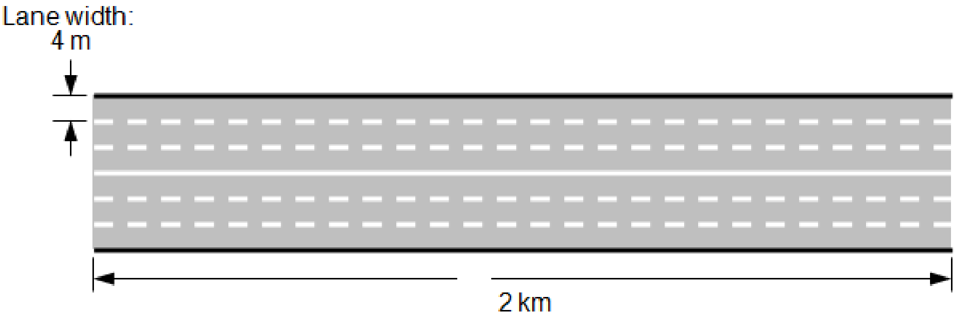

*Figure 17: Road configuration for motorway evaluation scenario.*

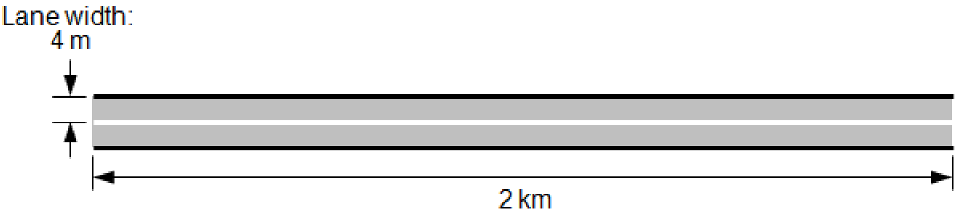

*Figure 18: Road configuration for rural evaluation scenario.*

*Table 19: Vehicle UE and pedestrian UE drop and mobility models.*

| Parameter | Urban case | Motorway case | Rural case |
|---|---|---|---|
| Number of lanes | 2 in each direction. 4 lanes in total in each street. | 3 in each direction. 6 lanes in total in the motorway. | 1 in each direction. 2 lanes in total in the rural roads. |
| Lane width | 3.5 m | 4 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 | N/A |
| Simulation area size | Area contains 14 urban 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. | 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. | 100, 110, 120, 130, 140 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 motorway | Equally spaced along the edge of the rural roads |
| Total number of pedestrian UEs | 500 | 10 | 20M (pedestrian clusters), where M is uniformly distributed between 2 and 3. |

| Parameter | Urban case | Motorway case | Rural case |
|---|---|---|---|
| Inter-pedestrian UE distance | 36.34 m[13] | 400 m[14] | 0 m for intra pedestrian cluster and 200 m for inter pedestrian cluster |
| Absolute pedestrian speed | 3 km/h | | |

### Wrap around model

The wrap around model for the urban, motorway, and rural evaluation scenarios are shown in Figure 19, Figure 20 and Figure 21.

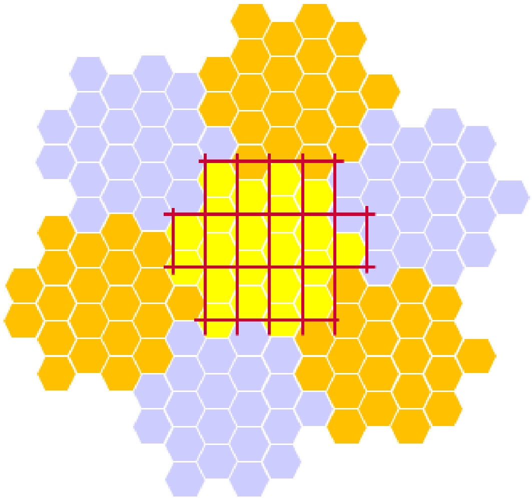

*Figure 19: Wrap around model for the urban evaluation scenario.*
*The sides of the hexagons are 500/3 metres long and the yellow area contains 14 urban grids each of dimension 433 by 250 metres.*

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[13] 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.

[14] The value is obtained by dividing the total motorway length by the total number of pedestrians, i.e., 2000 × 2 / 10 = 400 m.

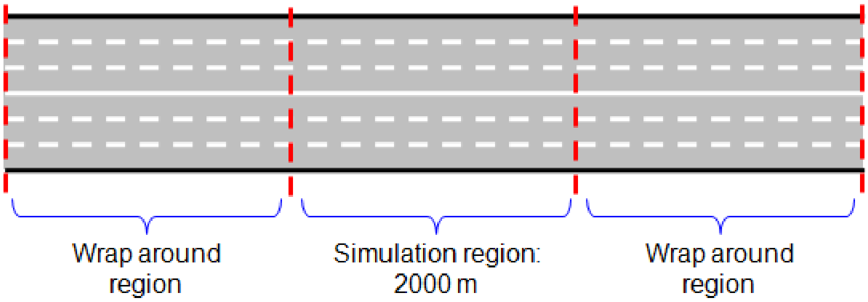

*Figure 20: Wrap around model for the motorway evaluation scenario.*

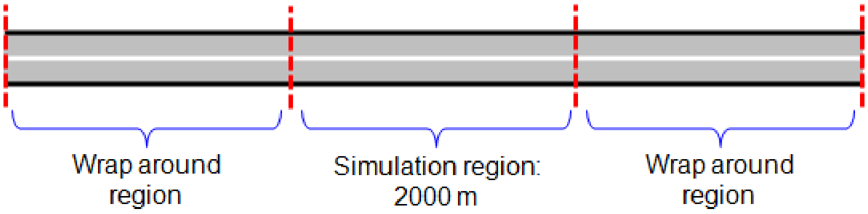

*Figure 21: Wrap around model for the rural evaluation scenario.*

### Channel models

The radio propagation channels modelled between vehicle UEs are described in Table 20.

*Table 20: Vehicle-to-vehicle channel model.*

| Parameter | Urban case | Motorway and 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 pathloss, 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

### Traffic model for V2V

Table 21 shows the parameters used for the generation of periodic V2V communications traffic.

*Table 21: 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 |
| Motorway | 100 – 140 | 100 | |
| Rural | 60 – 100 | 100 | |

*Note: The time instance for the generation of the 300-byte size messages is randomized among vehicles. The calculated packet reception ratio is the value averaged over the five messages.*

### 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.

### 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.

## C2. Performance evaluation results

The various system-level simulation assumptions and parameters for LTE-V2X (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-V2X (PC5) and 802.11p for motorway, urban and rural evaluation scenarios are presented in Figure 22 to Figure 33 below. Observe that LTE-V2X (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, 60 to 100 km/h for rural, and 100 to 140km/h for motorway), which can be attributed to both link-level and system-level gains.

At the link level, LTE-V2X (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-V2X (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.

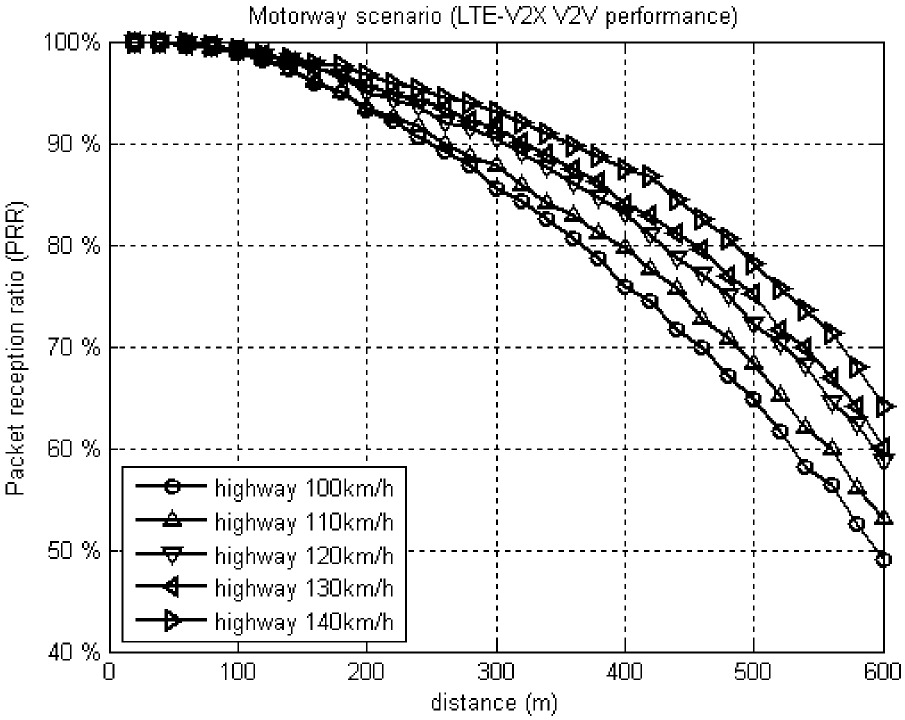

*Figure 22: LTE-V2V PRR performance in 6-lane motorway scenario.*

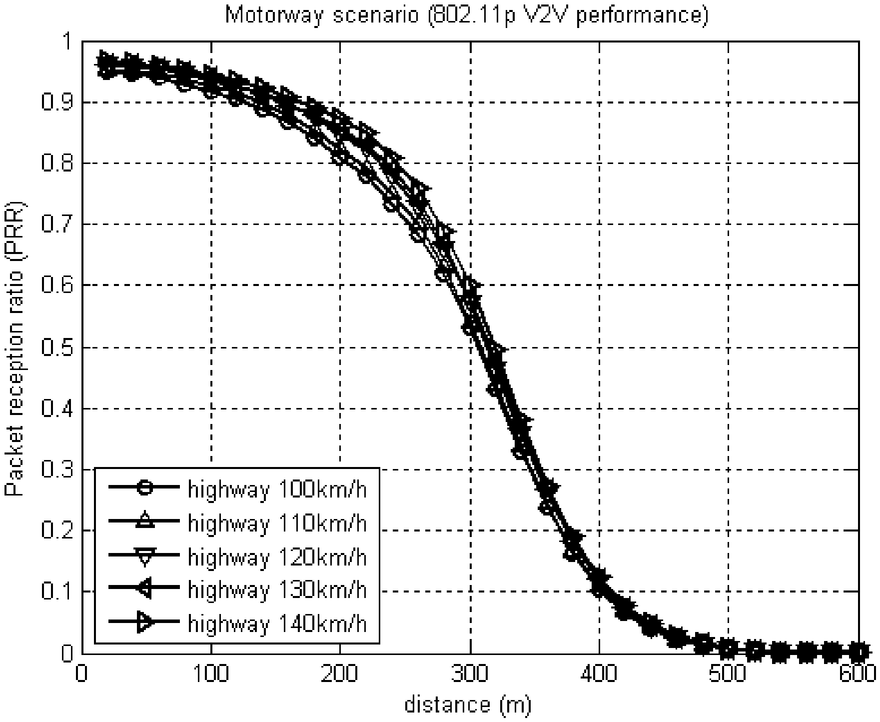

*Figure 23: 802.11p V2V PRR performance in 6-lane motorway scenario.*

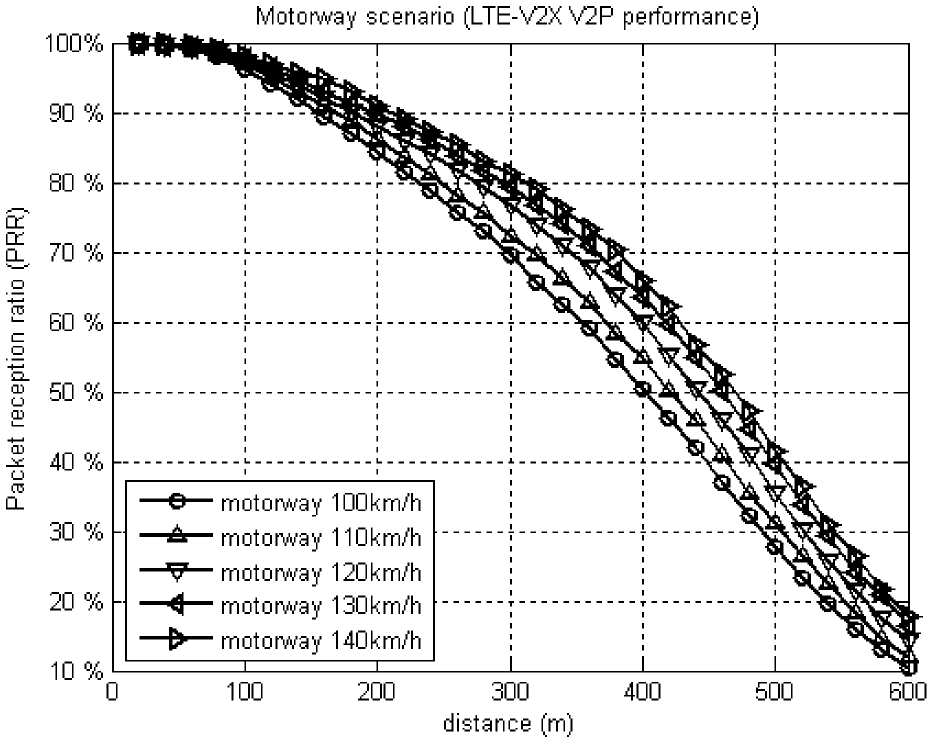

*Figure 24: LTE-V2P PRR performance in 6-lane motorway scenario.*

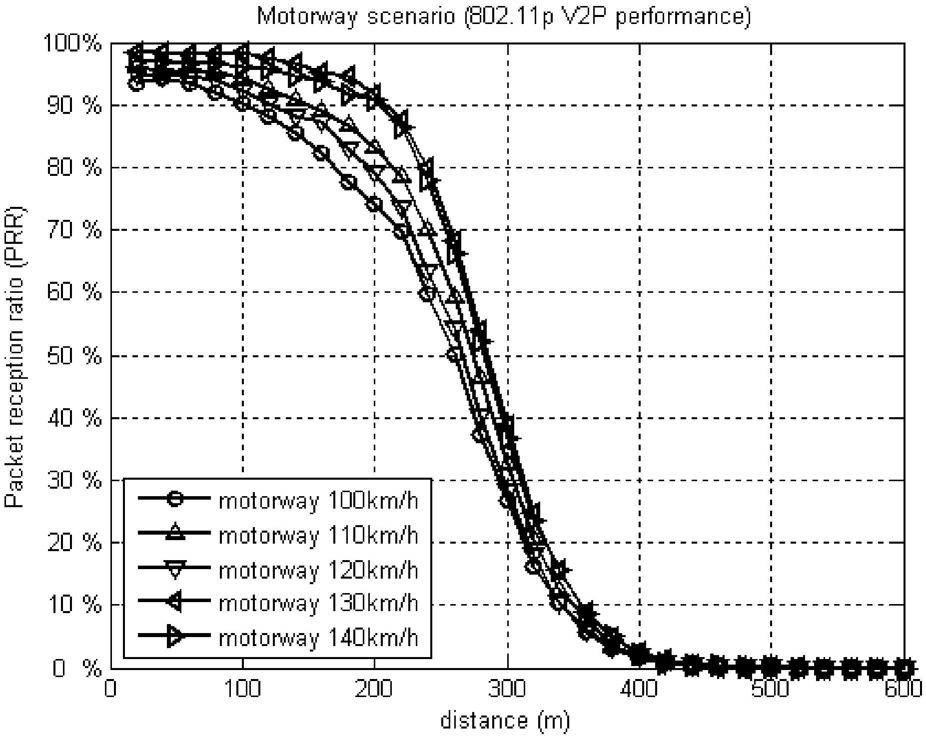

*Figure 25: 802.11p V2P PRR performance in 6-lane motorway scenario.*

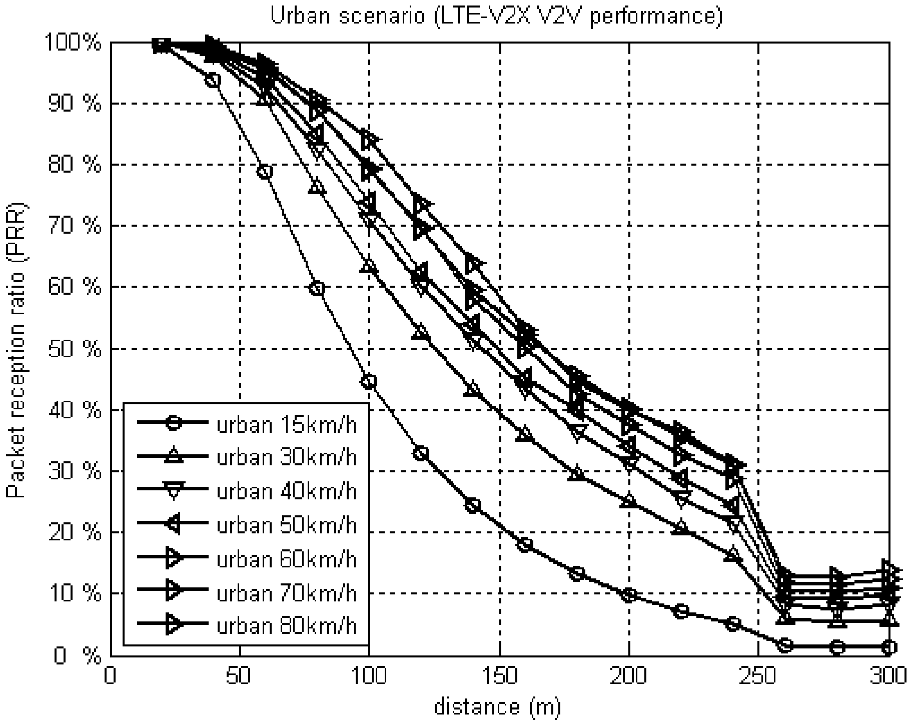

Figure 26: LTE-V2V PRR performance in urban grid scenario.

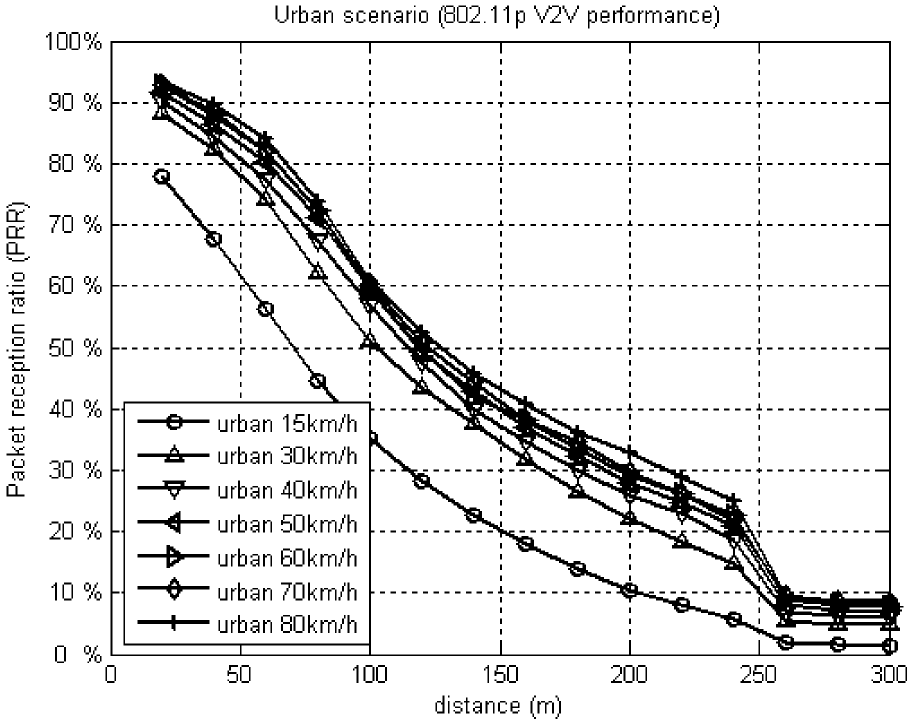

Figure 27: 802.11p V2V PRR performance in urban grid scenario.

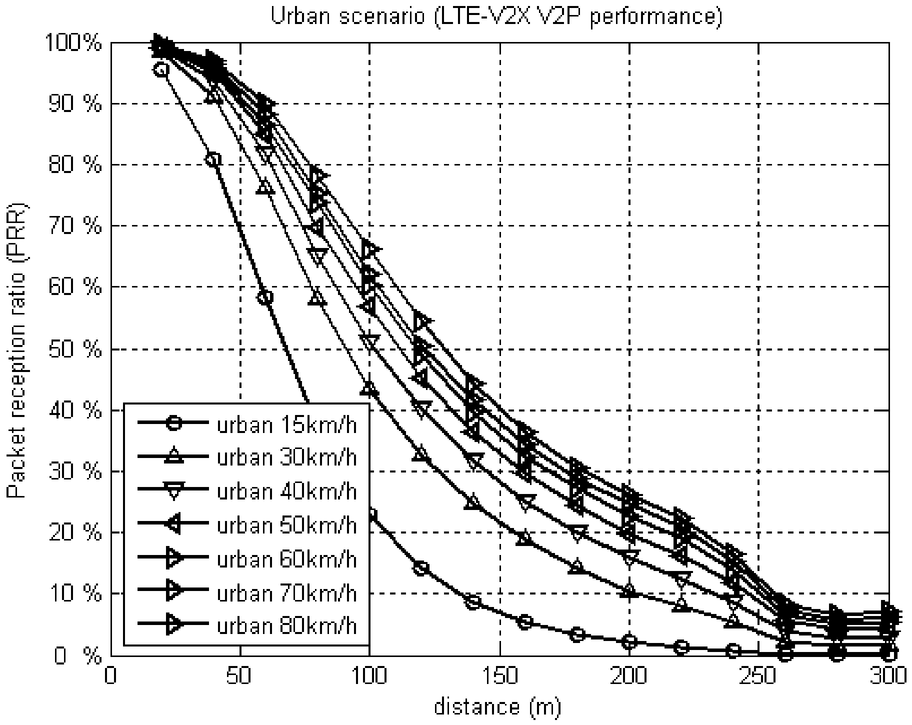

*Figure 28: LTE-V2P PRR performance in urban grid scenario.*

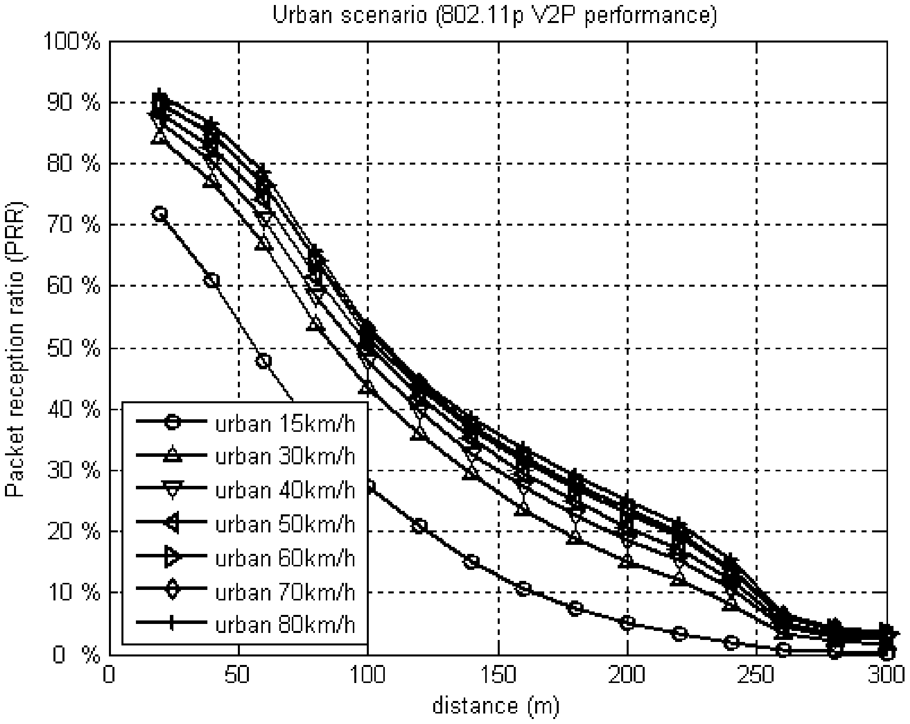

*Figure 29: 802.11p V2P PRR performance in urban grid scenario.*

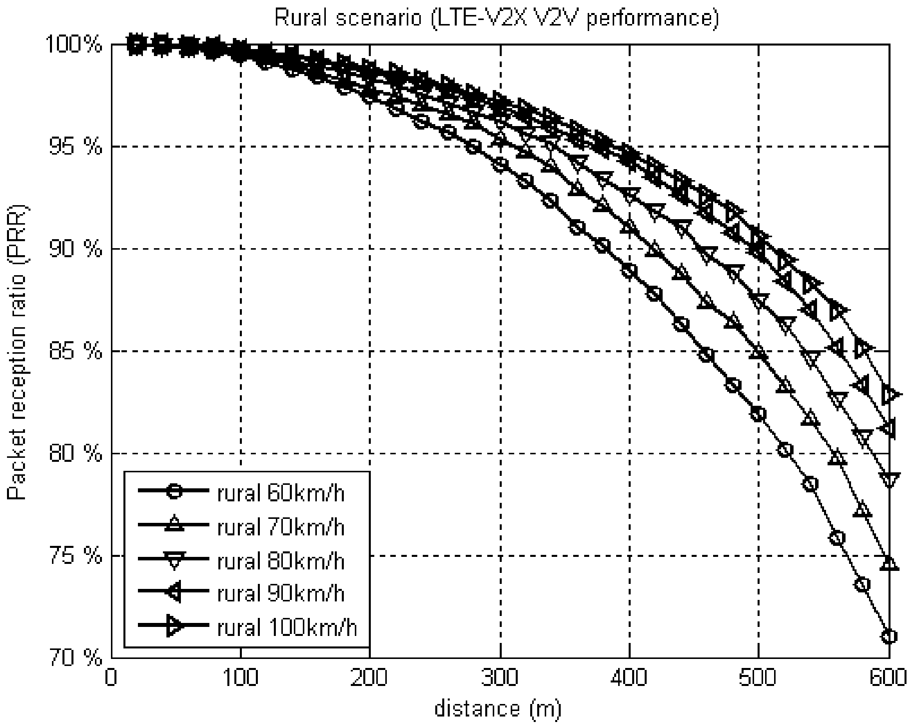

*Figure 30: LTE-V2V PRR performance in 2-lane rural scenario.*

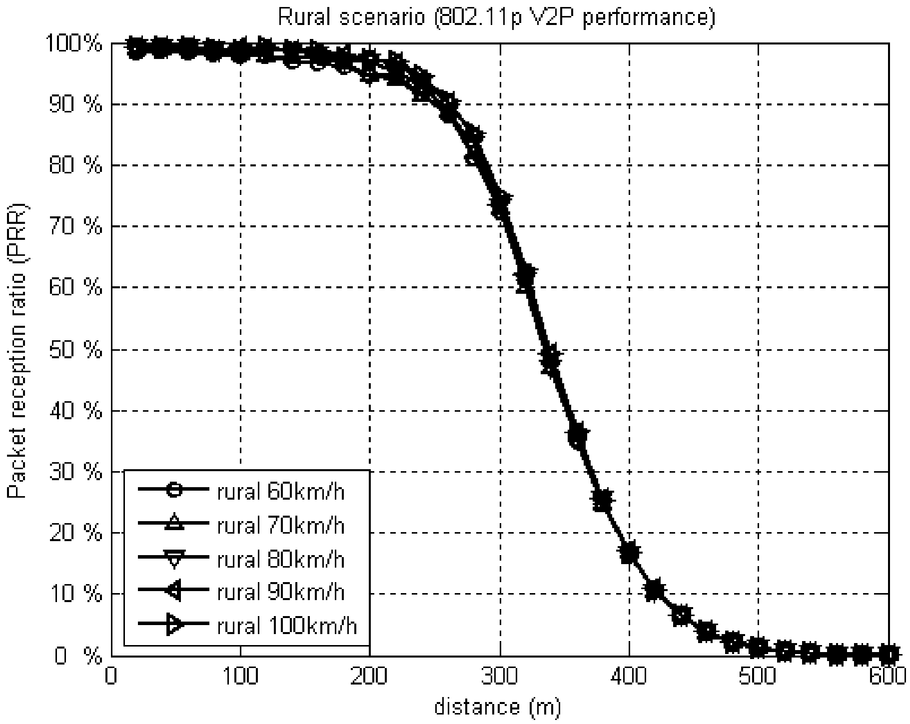

*Figure 31: 802.11p V2V PRR performance in 2-lane rural scenario.*

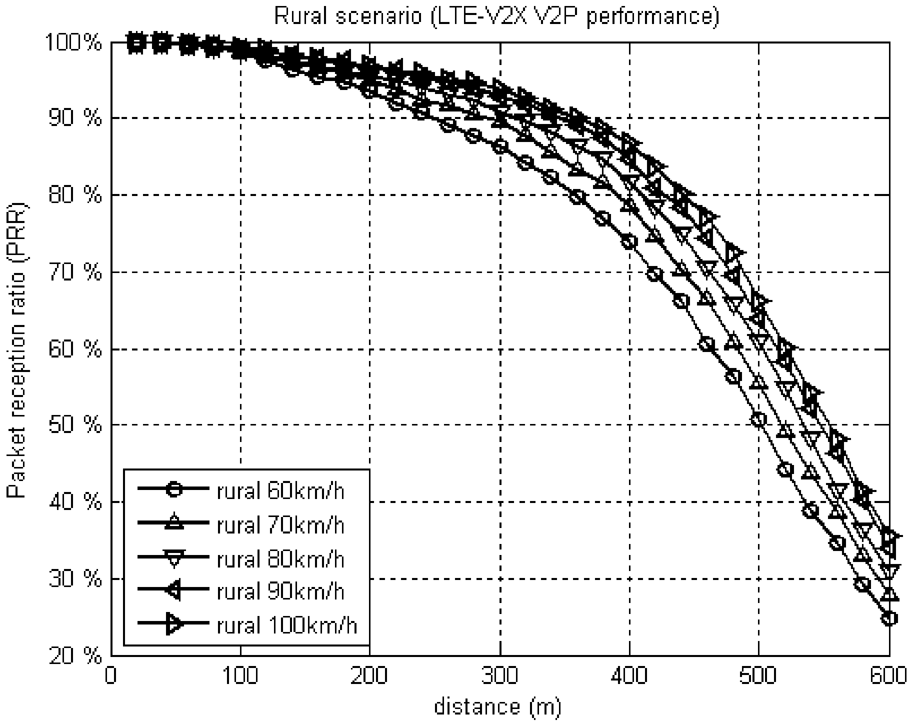

*Figure 32: LTE-V2P PRR performance in 2-lane rural scenario.*

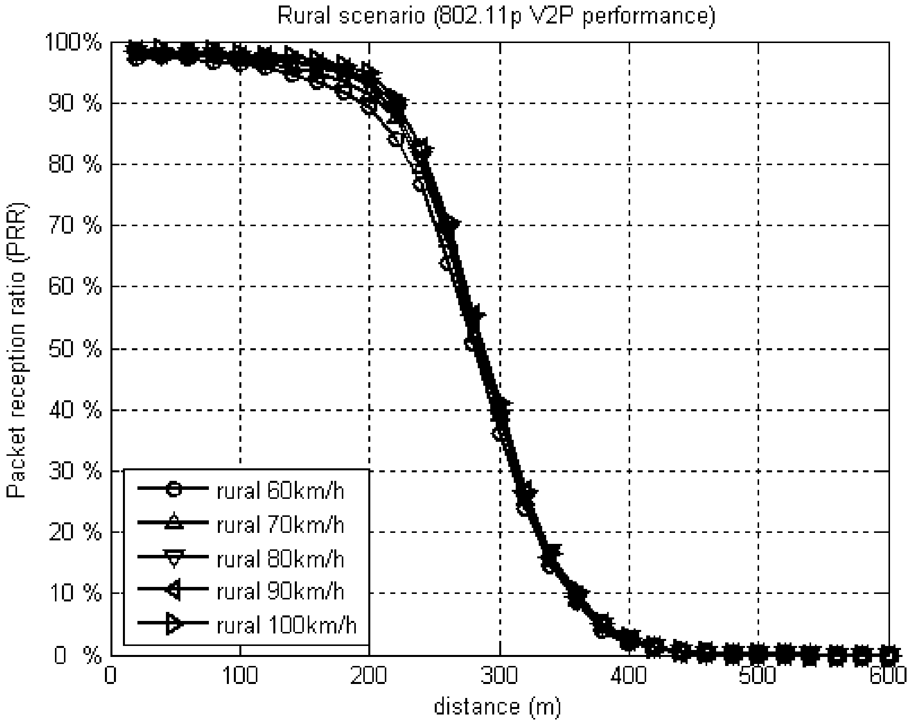

*Figure 33: 802.11p V2P PRR performance in 2-lane rural scenario.*

## C3. Link between system-level evaluation scenarios and modelled accident scenarios

### Link with modelled accident scenarios

The evaluation scenarios described above have been used to calculate the alert delivery reliability for LTE-V2X (PC5) and 802.11p. Table 22 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 22: 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<br>Vehicle / motorbike | Grid/urban scenario V2V performance | 15 - 40 |
| | Junction | Vehicle / pedestrian<br>Vehicle / cyclist | Grid/urban scenario V2 smartphone performance | 15 - 40 |
| | Not at junction | Vehicle / vehicle<br>Vehicle / motorbike | Grid/urban scenario V2V performance | 20 – 60 |
| | Not at junction | Vehicle / pedestrian<br>Vehicle / cyclist | Grid/urban scenario V2 smartphone performance | 20 – 60 |
| Rural | Junction | Vehicle / vehicle<br>Vehicle / motorbike | Grid/urban scenario V2V performance | 50 – 80 |
| | Junction | Vehicle / pedestrian<br>Vehicle / cyclist | Grid/urban scenario V2 smartphone performance | 50 – 80 |
| | Not at junction | Vehicle / vehicle<br>Vehicle / motorbike | 2-lane rural scenario V2V performance | 50 – 100 |
| | Not at junction | Vehicle / pedestrian<br>Vehicle / cyclist | 2-lane rural scenario V2 smartphone performance | 50 – 100 |
| Motorways | Not at junction | Vehicle / vehicle<br>Vehicle / motorbike | 6-lane motorway scenario V2V performance | 70 – 140 |
| | Not at junction | Vehicle / pedestrian<br>Vehicle / cyclist | 6-lane motorway scenario V2 smartphone performance | 70 – 140 |

### AASHTO model, safe stopping distance and reliability at a specific speed

Using the outputs from the evaluation scenarios as plotted in Figure 22 to Figure 33, 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 [28] 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:

*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 |

### 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 34 to Figure 45 below present extrapolated values of alert delivery reliability rates as a function of speed for LTE-V2X (PC5) and 802.11p in the accident environments of interest.

## LTE-V2X (PC5): Not at junction – Motorway V2V/V2M

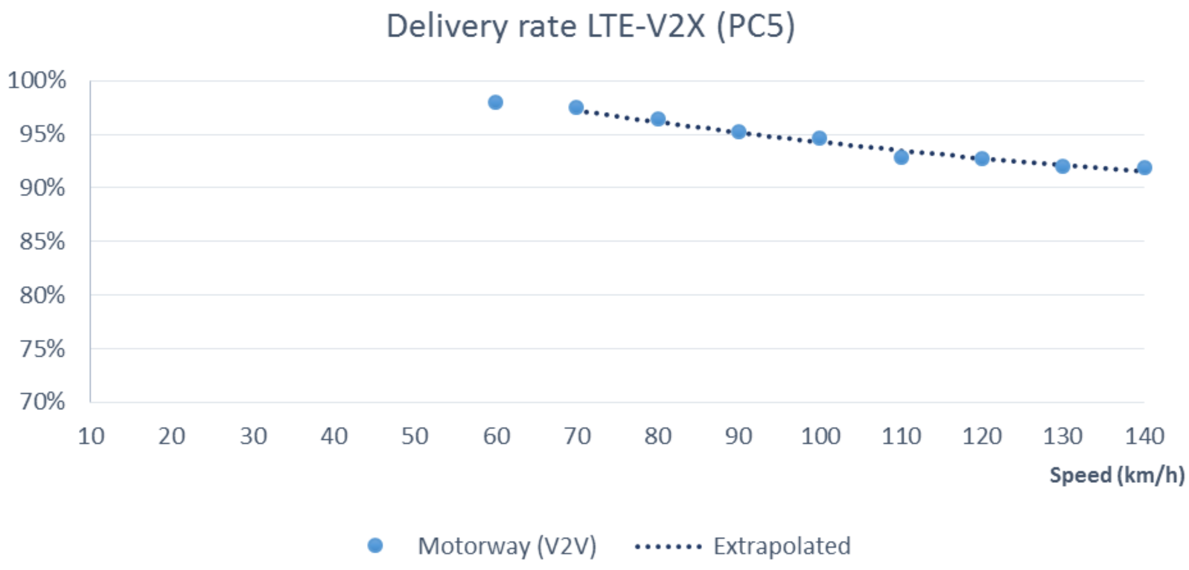

*Figure 34: LTE-V2V alert delivery reliability – not at junction model – motorway. Average over 70-140 km/h for Motorway V2V/V2M.*

## LTE-V2X (PC5): Not at junction – Motorway V2P

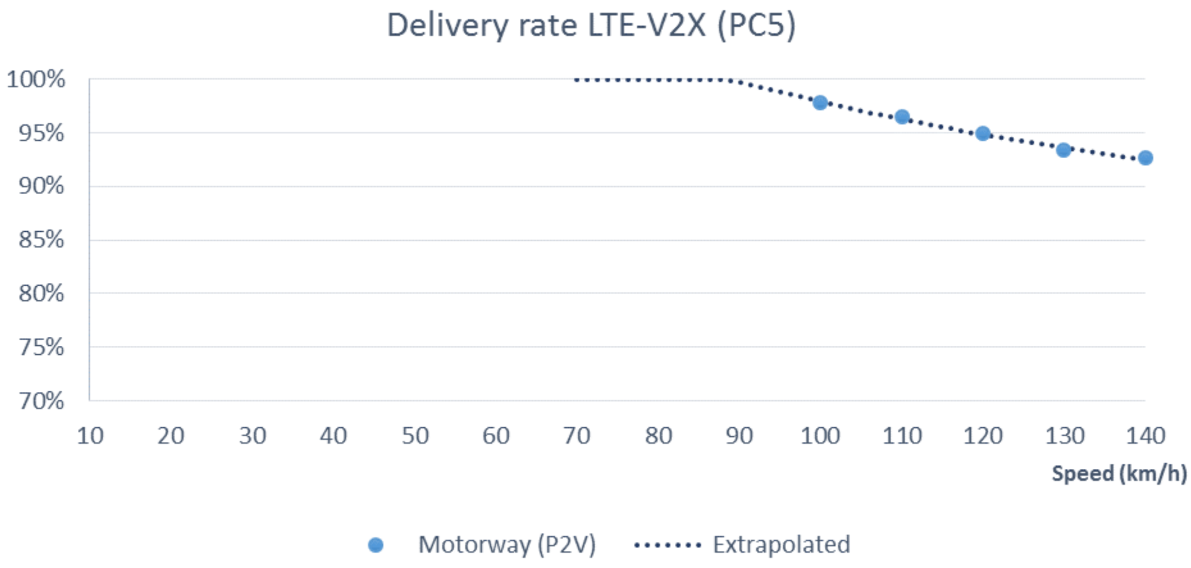

*Figure 35: LTE-V2P alert delivery reliability – not at junction model – motorway. Average over 70-140 km/h for motorway V2P.*

### LTE-V2X (PC5): Not at junction – Rural V2V/V2M

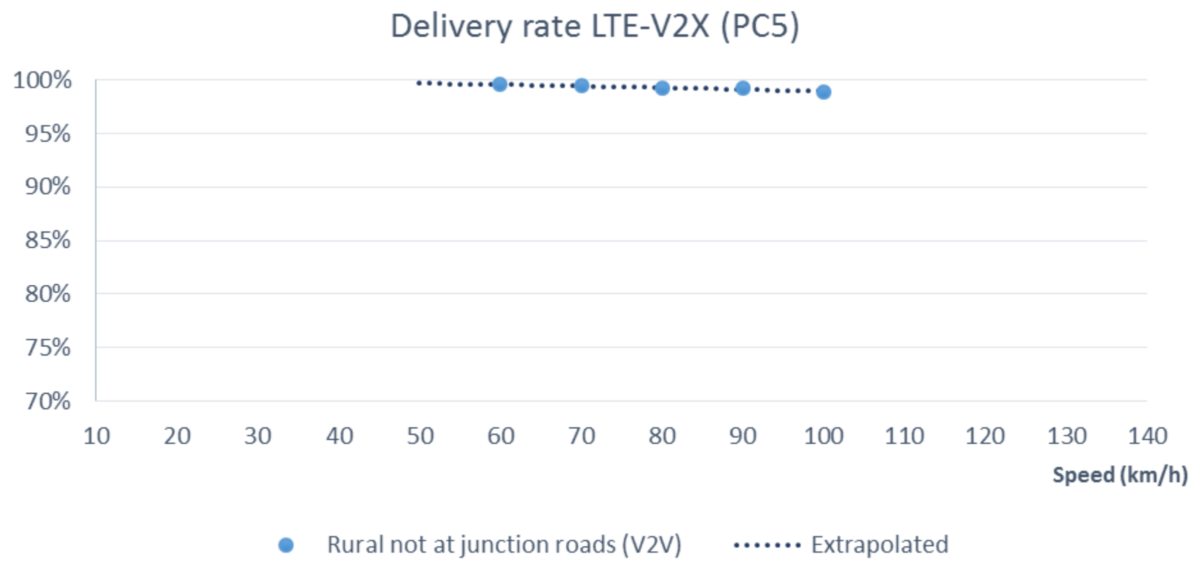

*Figure 36: LTE-V2V (PC5) alert delivery reliability – not at junction model – rural. Average over 50-100 km/h for rural V2V/V2M.*

### LTE-V2X (PC5): Not at junction – Rural V2P

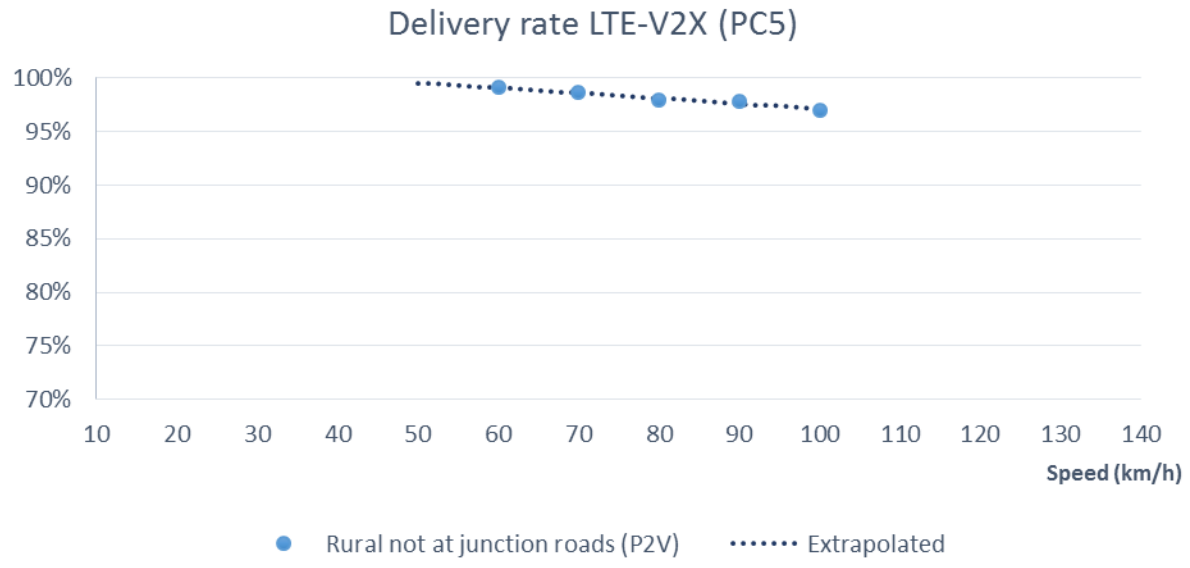

*Figure 37: LTE-V2P alert delivery reliability – not at junction model – rural. Average over 50 to 100 km/h for rural V2P.*

### LTE-V2X (PC5): Junction (grid) – Urban V2V/V2M

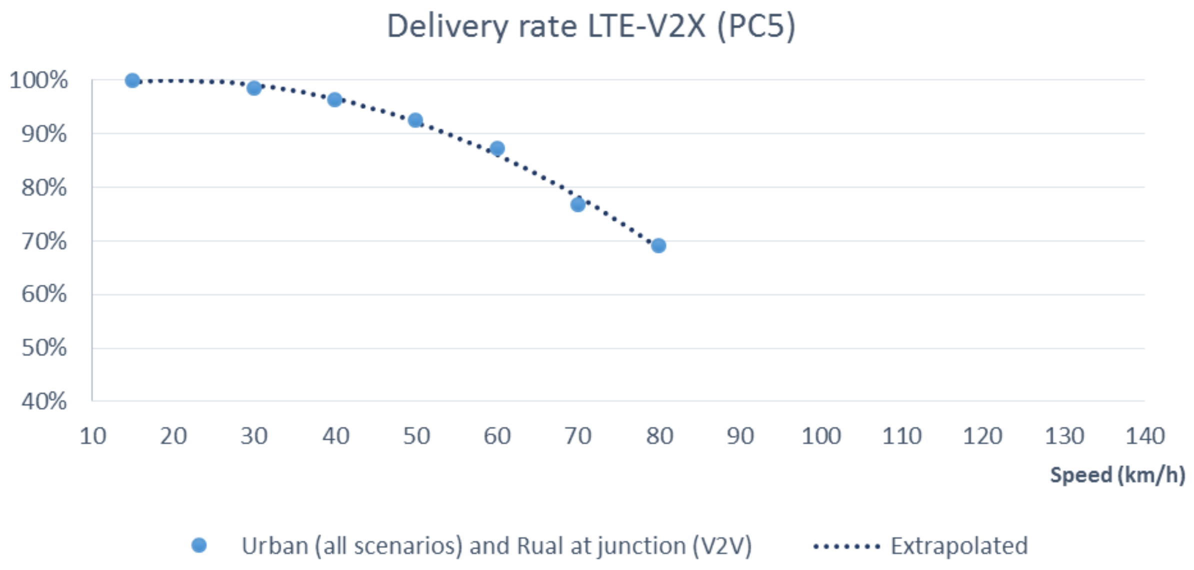

*Figure 38: LTE-V2V (PC5) alert delivery reliability – junction model – urban. Average over 15-40 km/h for urban at junction V2V/V2M. Average over 50-80 km/h for V2V/V2M rural at junction. Average over 20-60 km/h for urban not at junction V2V/V2M.*

### LTE-V2X (PC5): Junction (grid) – Urban V2P

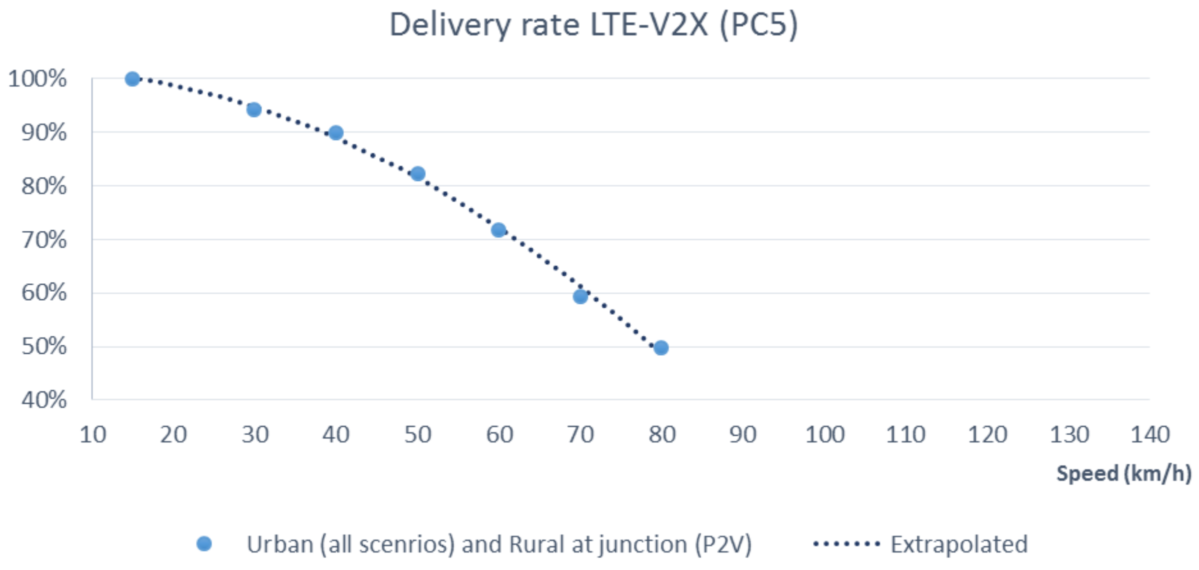

*Figure 39: LTE-V2P (PC5) alert delivery reliability – Junction model – urban. Average over 15-40 km/h for urban V2P. Average over 50-80 km/h for V2P rural at junction. Average over 20-60 km/h for urban not at junction V2P.*

### 802.11p: Not at junction – Motorway V2V/V2M

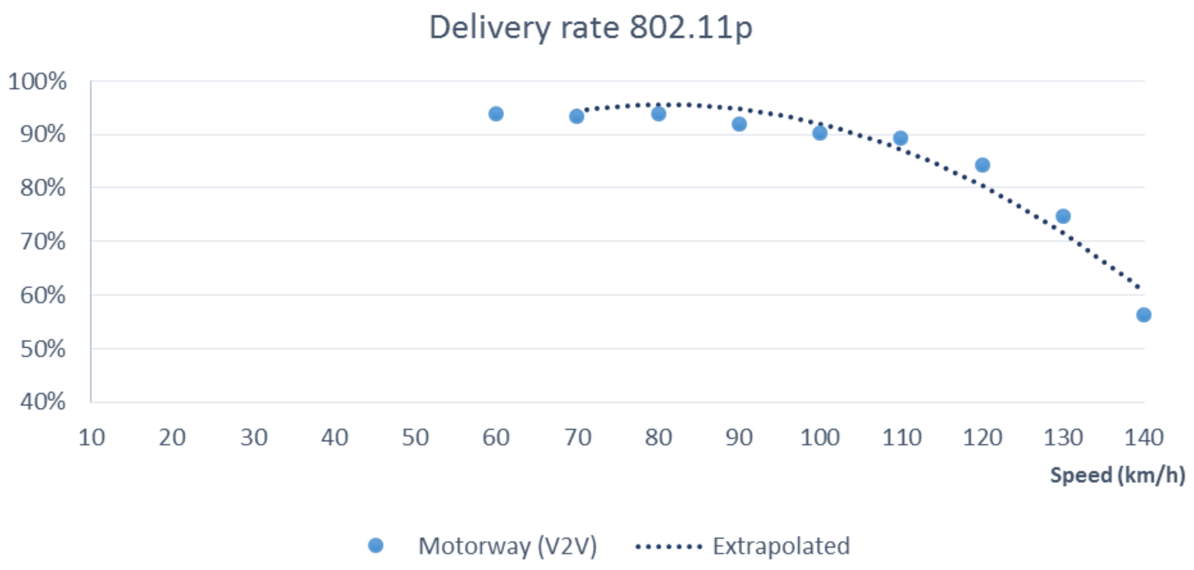

*Figure 40: 802.11p alert delivery reliability – not at junction model – motorway V2V. Average over 70-140 km/h for motorway V2V/V2M.*

### 802.11p: Not at junction – Motorway V2P

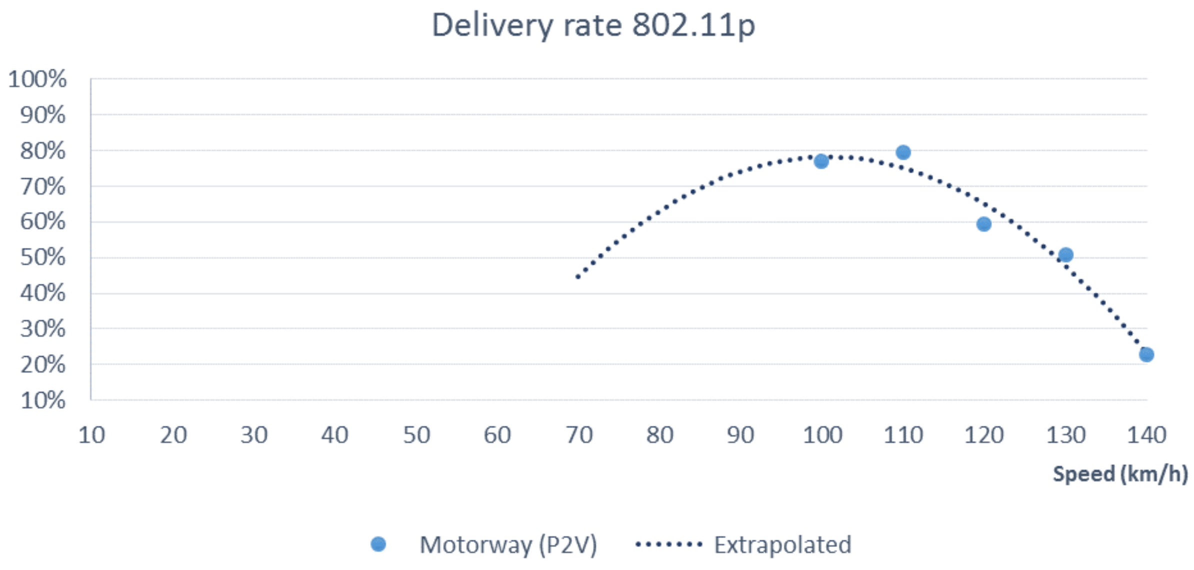

*Figure 41: 802.11p alert delivery reliability – not at junction model – motorway V2P. Average over 70-140 km/h for motorway V2P.*

### 802.11p: Not at junction – Rural V2V/V2M

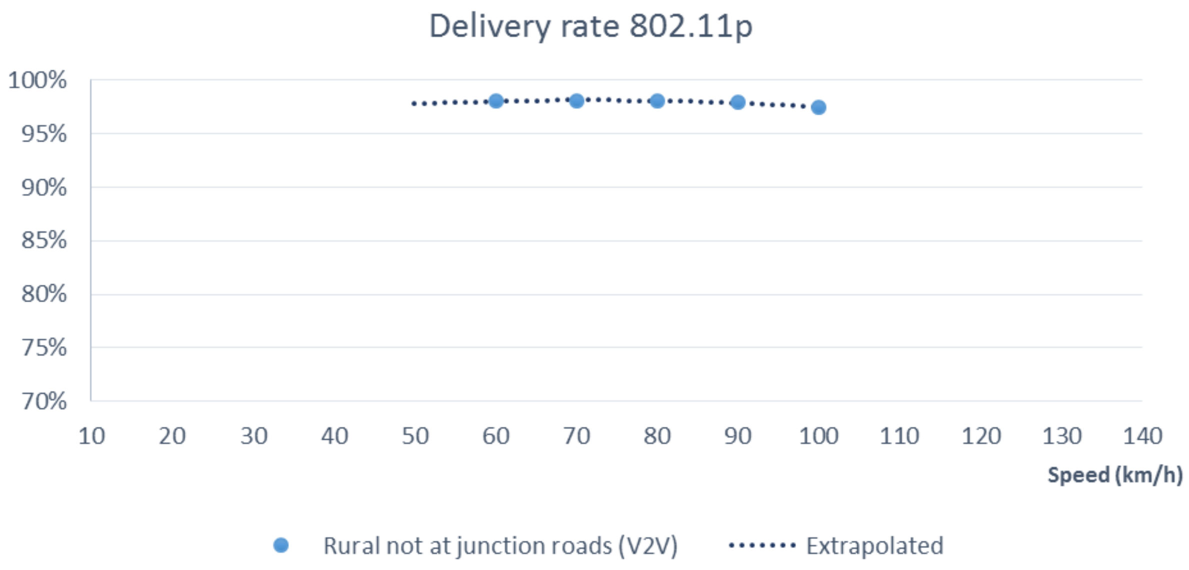

*Figure 42: 802.11p alert delivery reliability – not at junction model – rural V2V. Average over 50-100 km/h for rural V2V/V2M.*

### 802.11p: Not at junction – Rural V2P

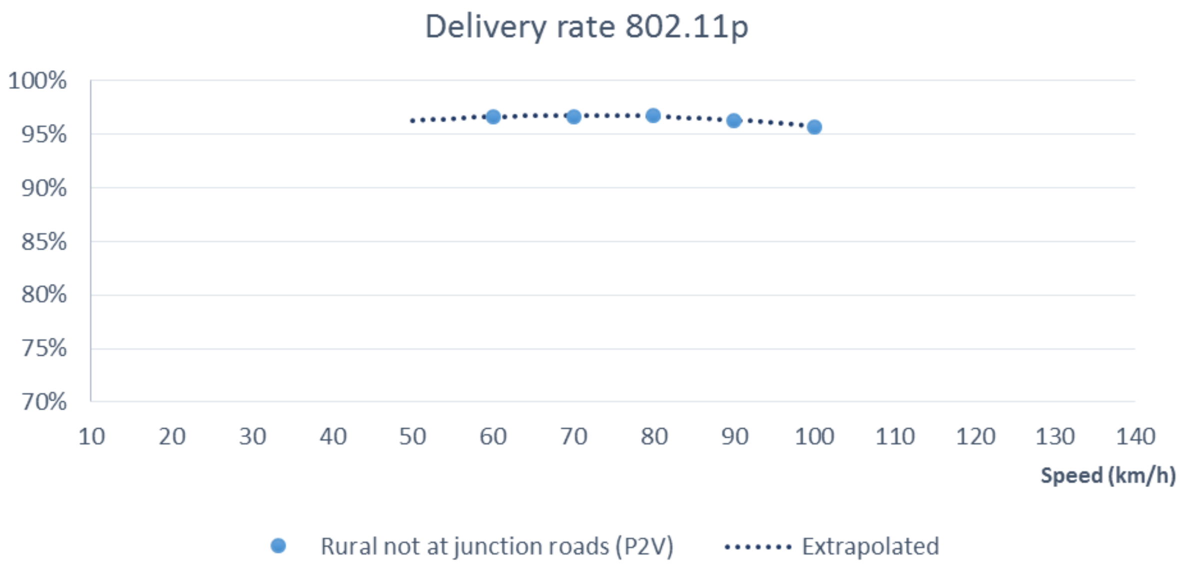

*Figure 43: 802.11p alert delivery reliability – not at junction model – rural V2P. Average over 50-100 km/h for rural V2P.*

**802.11p: Junction (grid) – Urban V2V/V2M**

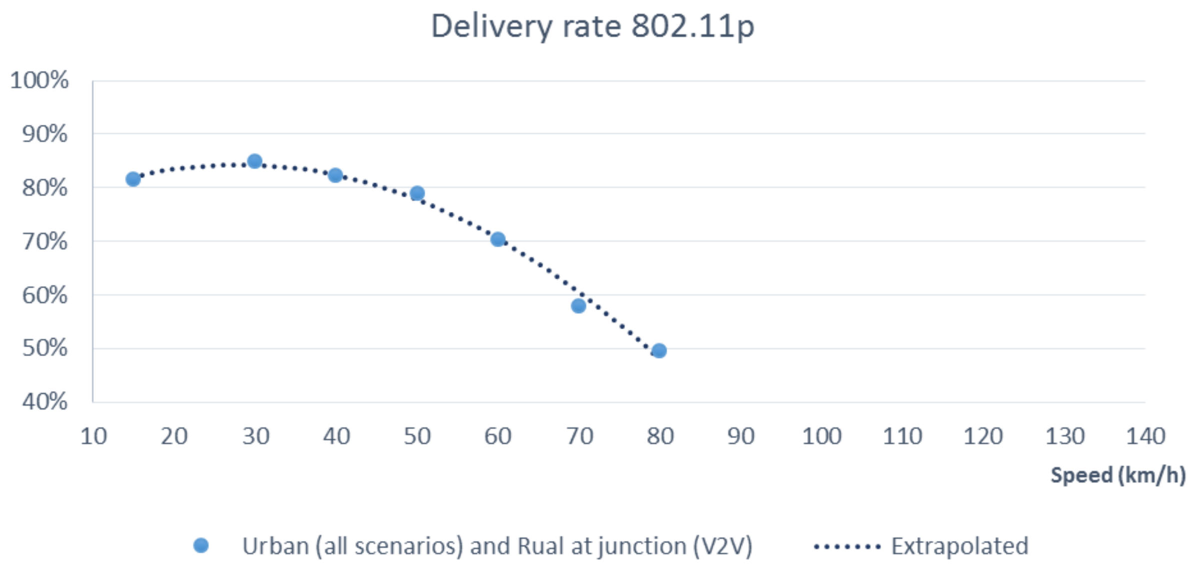

*Figure 44: 802.11p alert delivery reliability – junction model – urban V2V. Average over 15-40 km/h for urban at junction V2V/V2M. Average over 50-80 km/h for V2V/V2M rural at junction. Average over 20-60 km/h for urban not at junction V2V/V2M.*

**802.11p: Junction (grid) – Urban V2P**

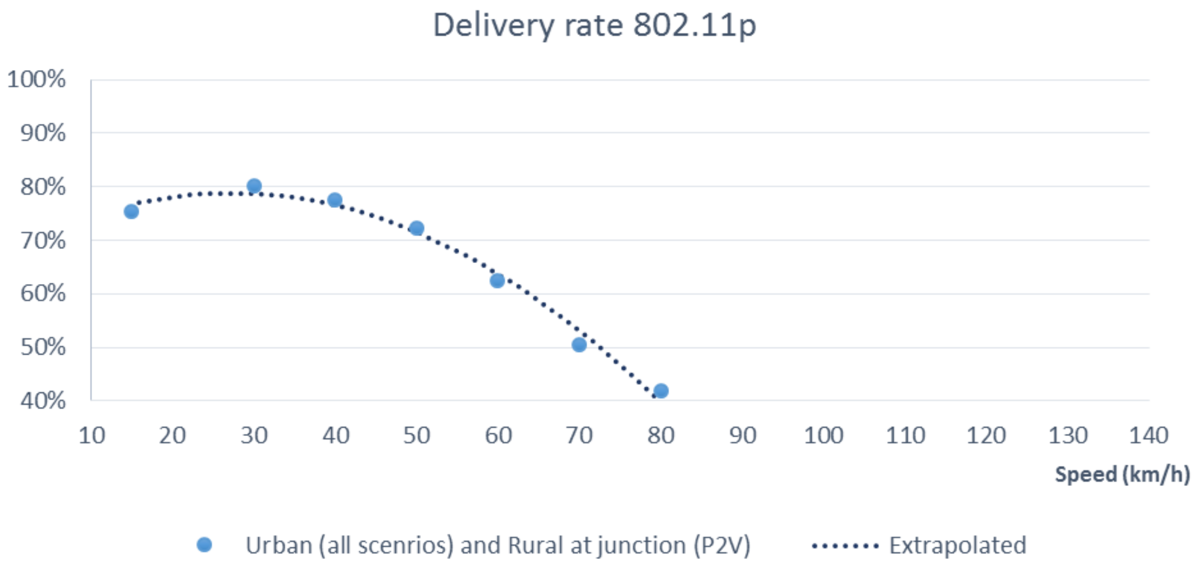

*Figure 45: 802.11p alert delivery reliability – junction model – urban V2P. Average over 15-40 km/h for urban V2P. Average over 50-80 km/h for rural V2P. Average over 20-60 km/h for urban V2P not at junction.*

The averaging of the reliability rates in Figure 34 to Figure 45 above over the appropriate ranges of speeds results in the alert delivery reliability rates used to represent the radio performance of LTE-V2X (PC5) and 802.11p for the accident scenarios modelled in this report. These are presented in Table 23 and Table 24 below.

*Table 23: Alert delivery reliability rates for LTE-V2X (PC5).*

| LTE-V2X (PC5) | At junction | | | Not at junction | | |
|---|---|---|---|---|---|---|
| V2 | Urban | Rural | Motorway | Urban | Rural | Motorway |
| Pedestrian | 95.7% | 67.3% | N/A | 88.37% | 98.40% | 97.02% |
| Bicycles | 95.7% | 67.3% | N/A | 88.37% | 98.40% | 97.02% |
| Motorcycles | 95.7% | 82.5% | N/A | 95.59% | 99.37% | 94.14% |
| Vehicles | 95.7% | 82.5% | N/A | 95.59% | 99.37% | 94.14% |

*Table 24: Alert delivery reliability rates for 802.11p.*

| 802.11p | At junction | | | Not at junction | | |
|---|---|---|---|---|---|---|
| V2 | Urban | Rural | Motorway | Urban | Rural | Motorway |
| Pedestrian | 78.0% | 58.6% | N/A | 74.8% | 96.5% | 62.5% |
| Bicycles | 78.0% | 58.6% | N/A | 74.8% | 96.5% | 62.5% |
| Motorcycles | 78.0% | 65.7% | N/A | 80.7% | 98.0% | 86.0% |
| Vehicles | 78.0% | 65.7% | N/A | 80.7% | 98.0% | 86.0% |

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.

# Annex D: Effectiveness of alert signals

The values used for the modelling of the effectiveness of alert signals in this report are obtained from the Drive C2X study [16] and are presented in Table 25.

*Table 25: Effectiveness of alert signals.*

|  | At junction |  |  | Not at junction |  |  |
|---|---|---|---|---|---|---|
| V2 | Urban | Rural | Motorway | Urban | Rural | Motorway |
| Pedestrian | 65.0% | 65.0% | 65.0% | 85.0% | 85.0% | 85.0% |
| Bicycles | 65.0% | 65.0% | 65.0% | 85.0% | 85.0% | 85.0% |
| Motorcycles | 65.0% | 68.3% | 65.0% | 71.7% | 77.5% | 78.3% |

# Annex E: Detailed results

*Figure 46: Avoided fatalities with LTE-V2X (PC5) in the high scenario.*

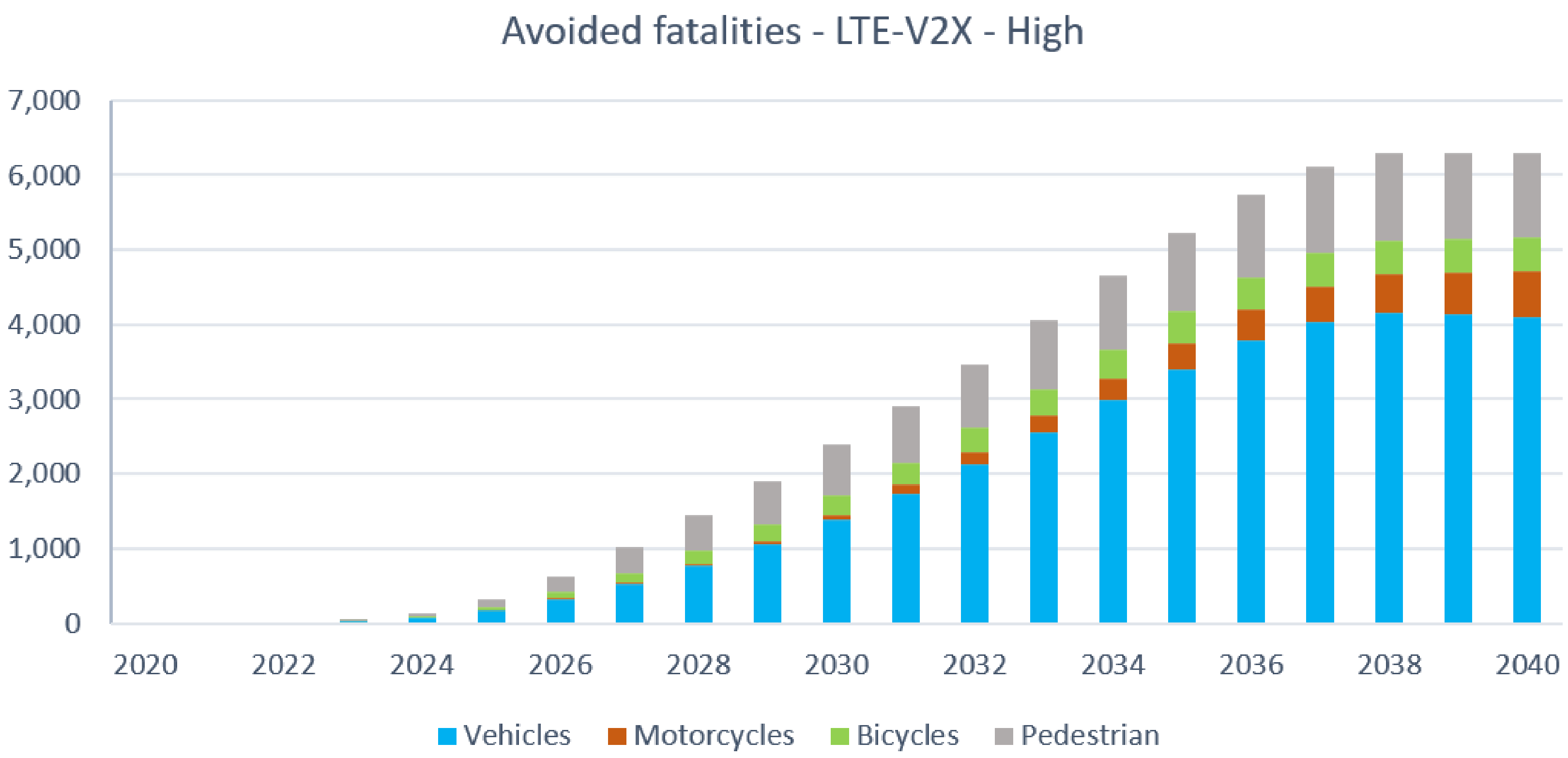

*Figure 47: Avoided serious injuries with LTE-V2X (PC5) in the high scenario.*

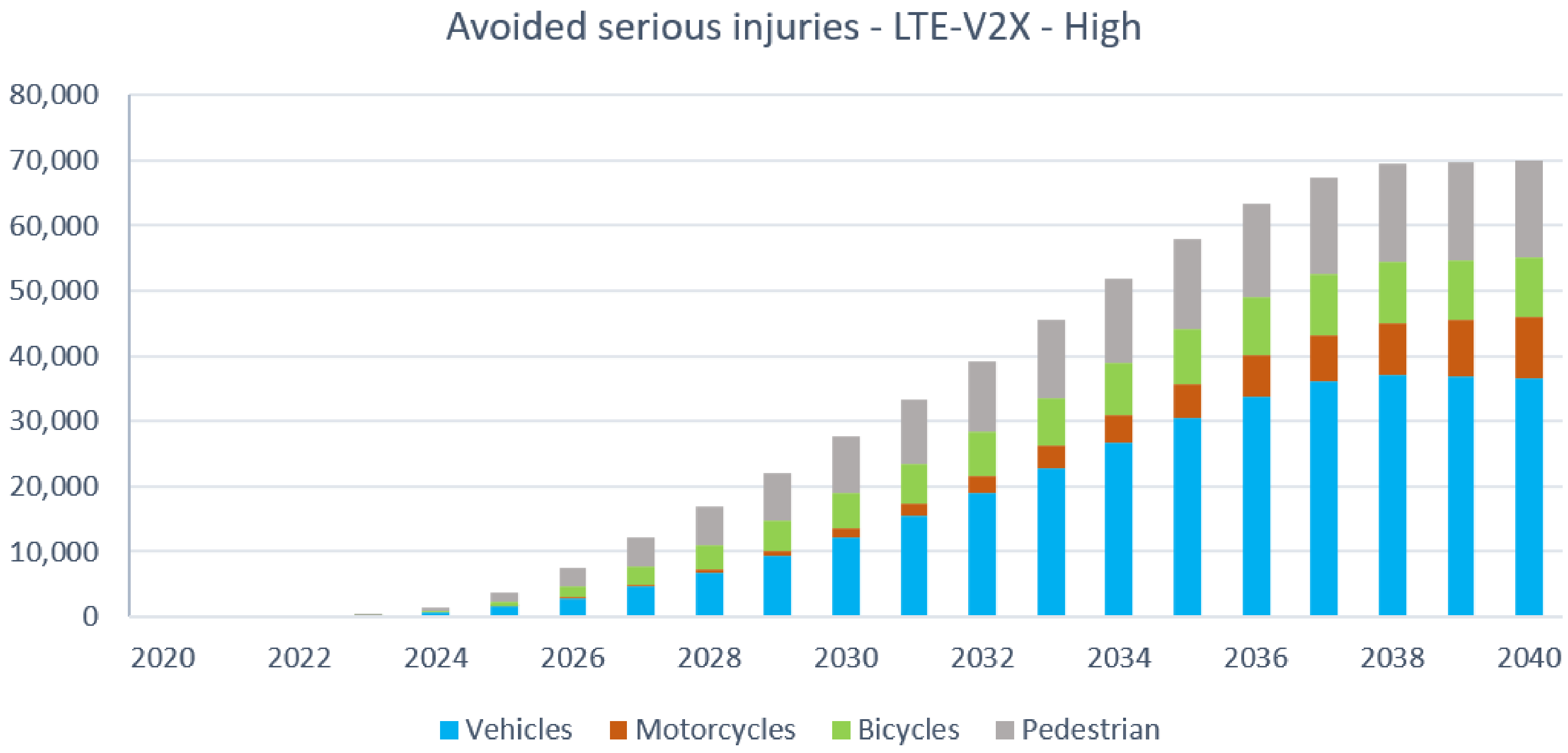

*Figure 48: Avoided fatalities with 802.11p in the high scenario.*

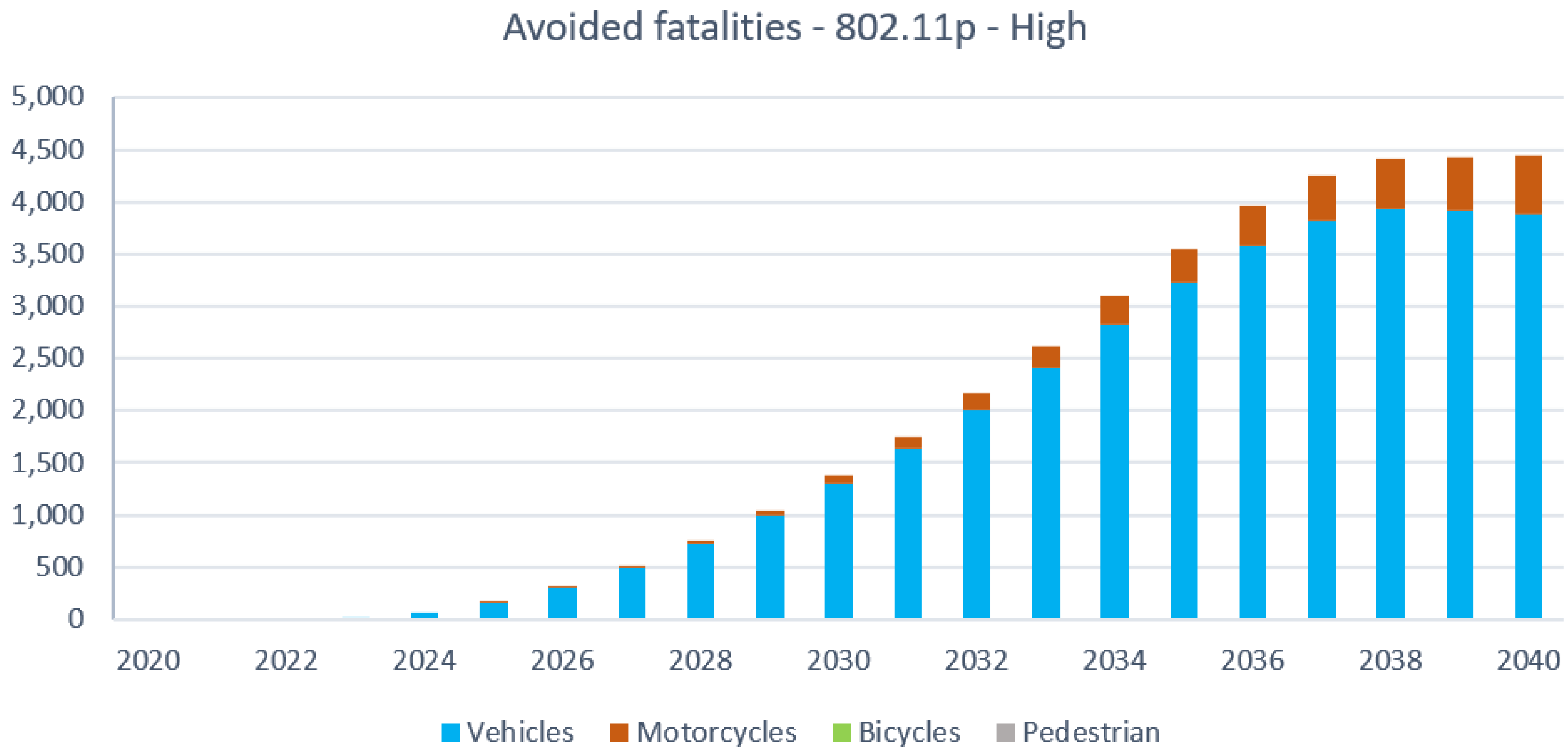

Figure 49: Avoided serious injuries with 802.11p in the high scenario.

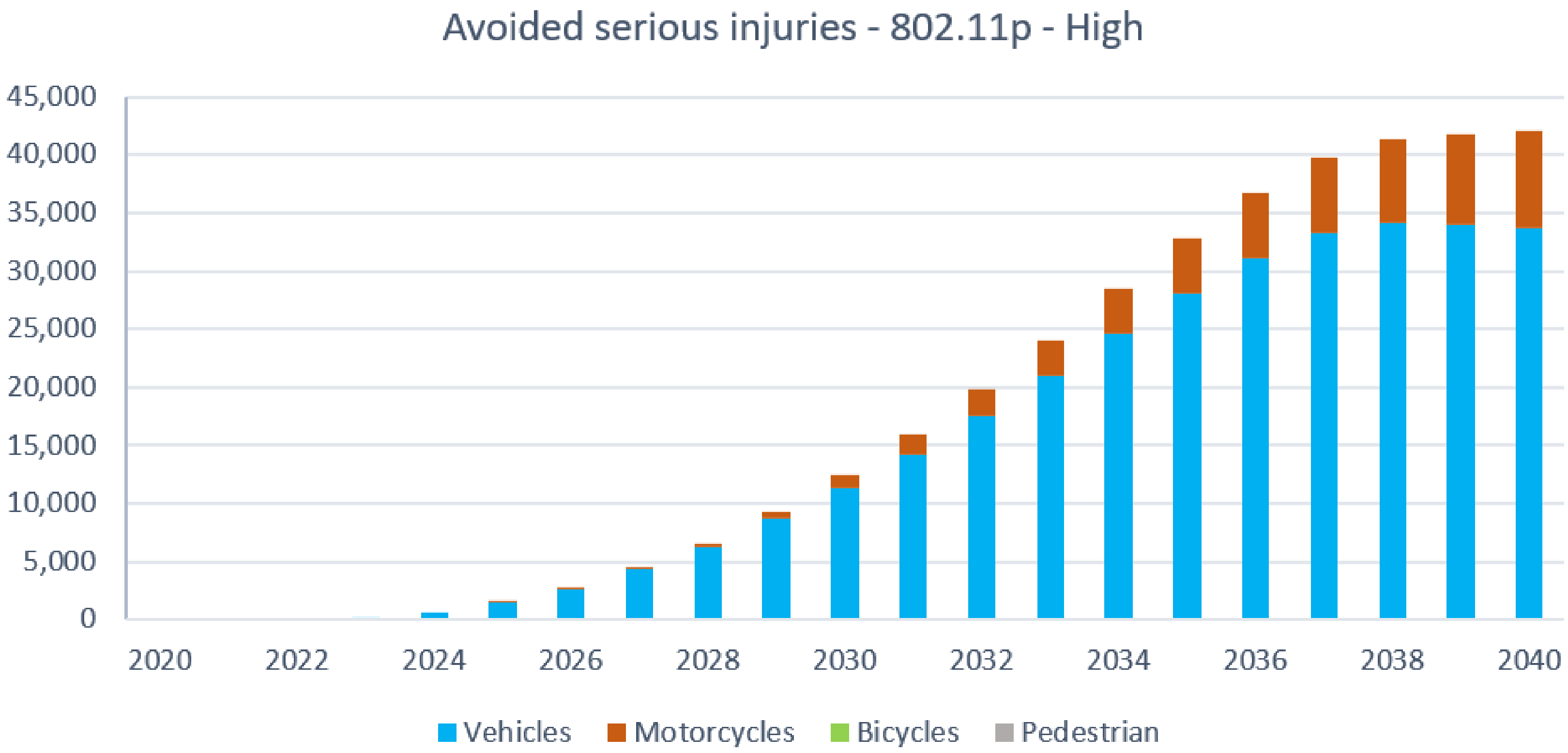

*Figure 50: Avoided fatalities with LTE-V2X (PC5) in the low scenario.*

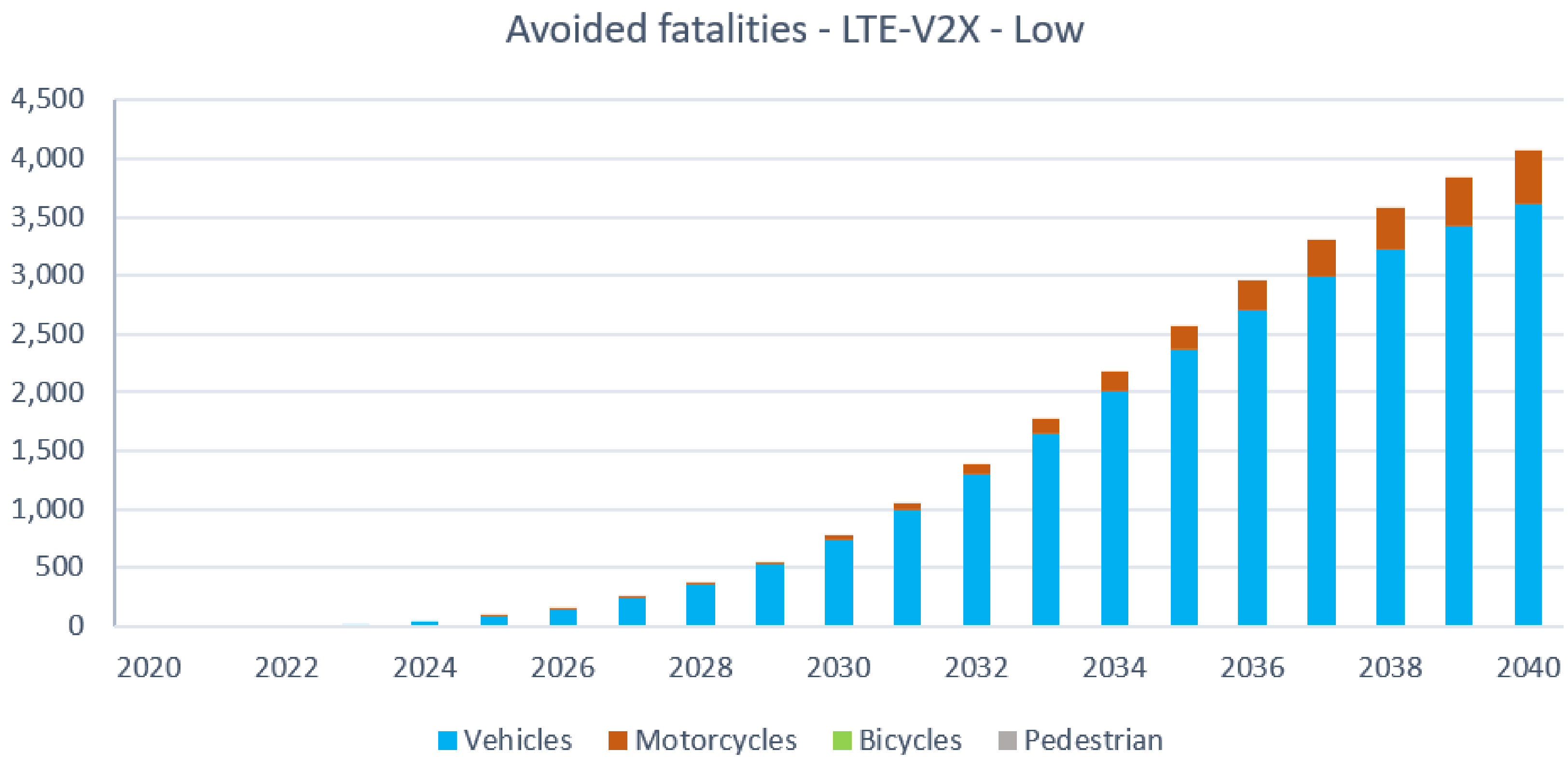

*Figure 51: Avoided serious injuries with LTE-V2X (PC5) in the low scenario.*

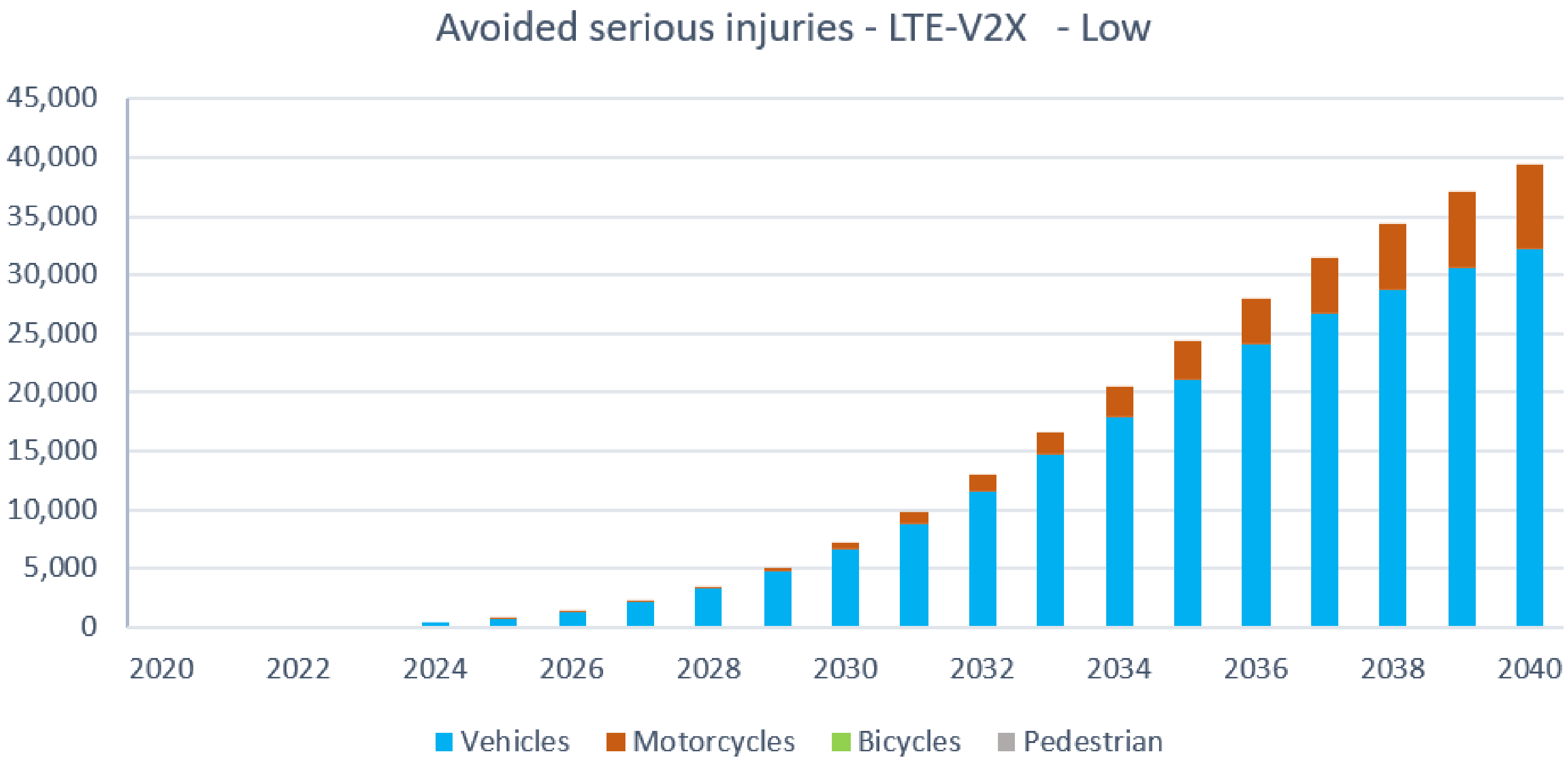

*Figure 52: Avoided fatalities with 802.11p in the low scenario.*

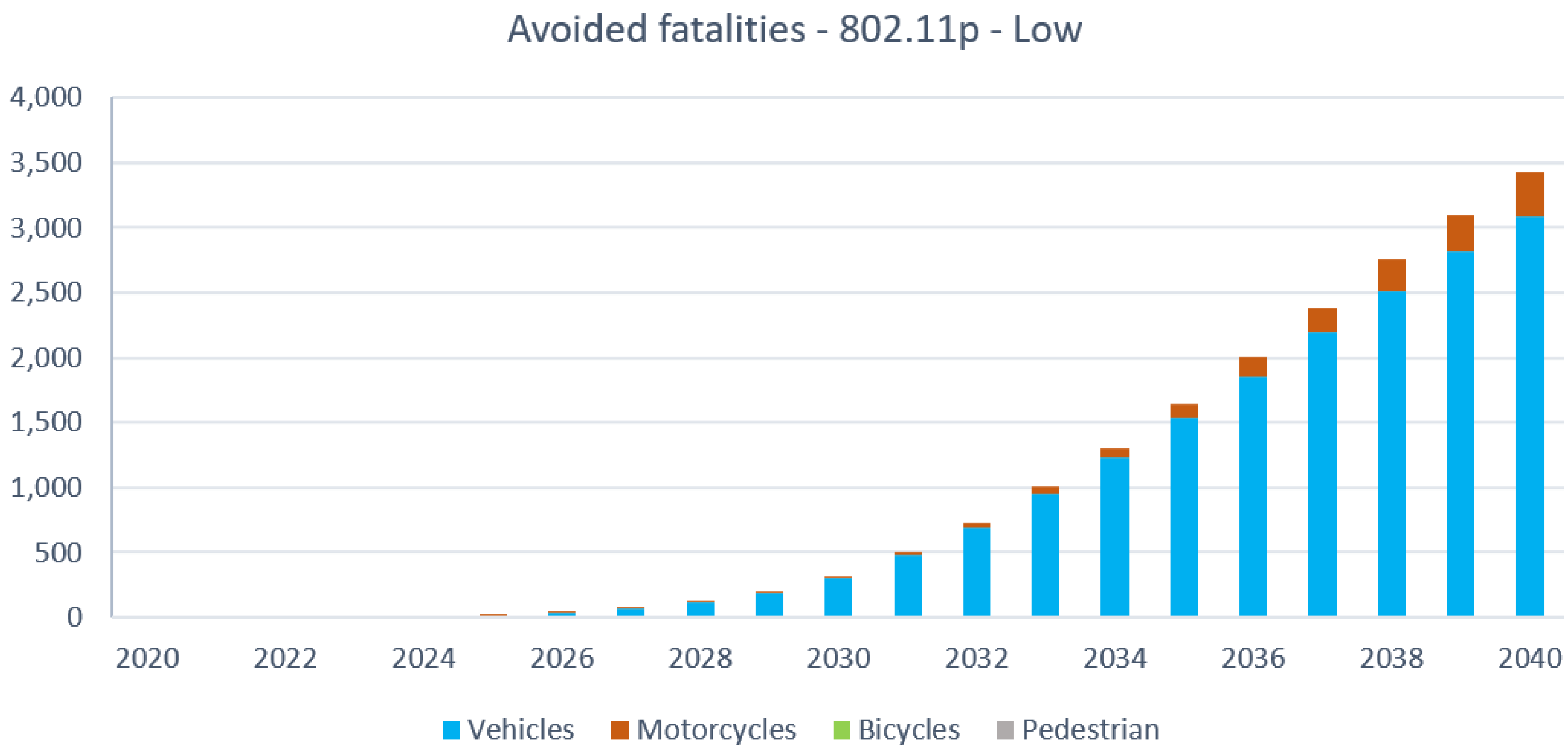

*Figure 53: Avoided serious injuries with 802.11p in the low scenario.*

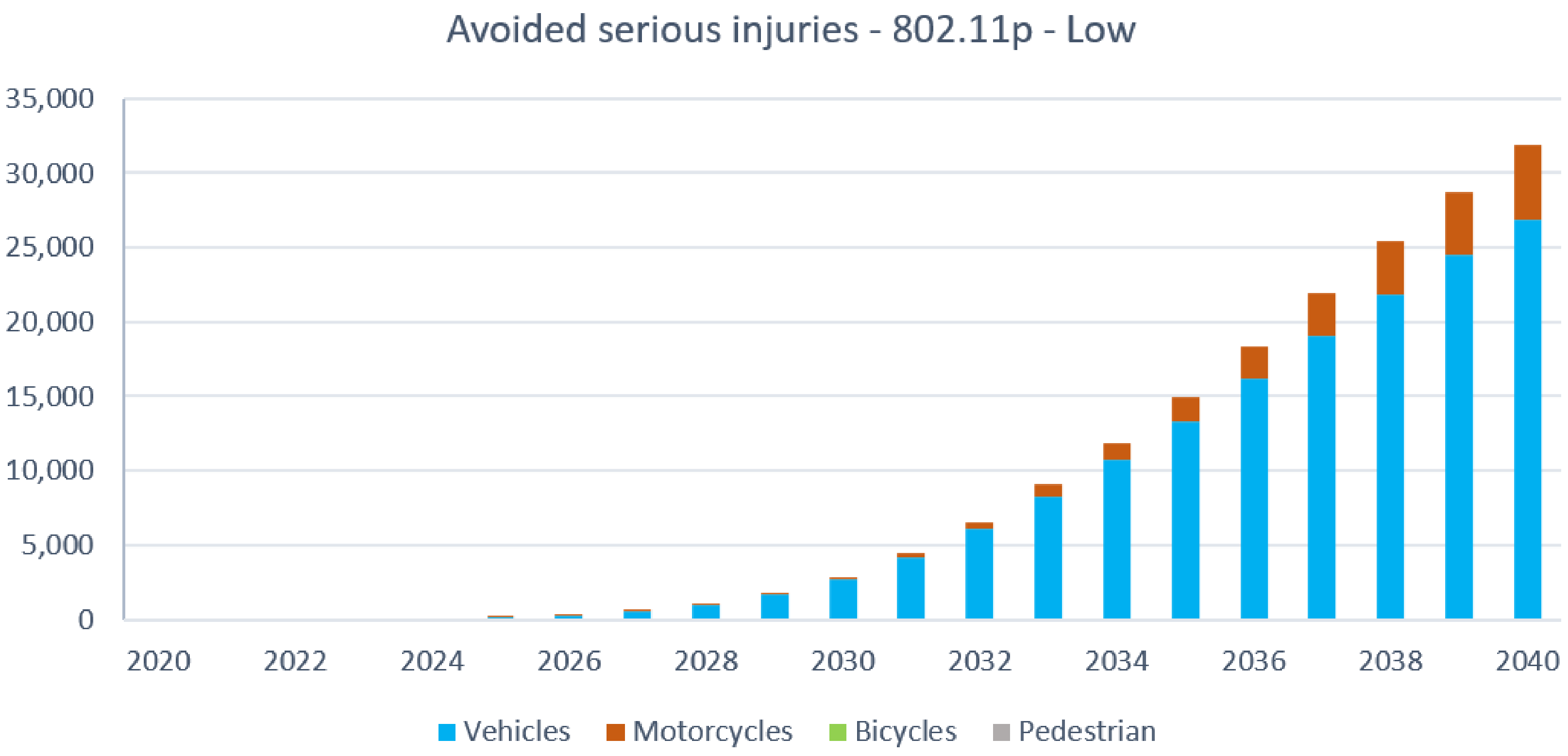

*Table 26: Number of fatalities and serious injuries avoided – high scenario – 2018 to 2029.*

| LTE-V2X (PC5) - High | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Total fatalities avoided | | | | | | | | | | | | |
| Category | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 |
| Pedestrian | 0 | 0 | 0 | 0 | 0 | 9 | 40 | 109 | 215 | 349 | 468 | 573 |
| Bicycles | 0 | 0 | 0 | 0 | 0 | 4 | 16 | 43 | 85 | 138 | 185 | 226 |
| Motorcycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 8 | 21 | 44 |
| Vehicles | 0 | 0 | 0 | 1 | 4 | 21 | 69 | 175 | 328 | 526 | 768 | 1,052 |
| Total | 0 | 0 | 0 | 1 | 4 | 33 | 125 | 328 | 630 | 1,021 | 1,441 | 1,895 |
| Total serious injuries avoided | | | | | | | | | | | | |
| Category | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 |
| Pedestrian | 0 | 0 | 0 | 0 | 0 | 116 | 524 | 1,416 | 2,790 | 4,530 | 6,069 | 7,438 |
| Bicycles | 0 | 0 | 0 | 0 | 0 | 72 | 325 | 878 | 1,729 | 2,808 | 3,761 | 4,610 |
| Motorcycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 41 | 125 | 324 | 680 |
| Vehicles | 0 | 0 | 0 | 7 | 40 | 188 | 614 | 1,561 | 2,927 | 4,695 | 6,854 | 9,390 |
| Total | 0 | 0 | 0 | 7 | 40 | 375 | 1,462 | 3,862 | 7,487 | 12,158 | 17,008 | 22,118 |
| 802.11p - High | | | | | | | | | | | | |
| Total fatalities avoided | | | | | | | | | | | | |
| Category | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 |
| Pedestrian | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bicycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Motorcycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 7 | 19 | 41 |
| Vehicles | 0 | 0 | 0 | 1 | 4 | 20 | 65 | 165 | 310 | 497 | 726 | 995 |
| Total | 0 | 0 | 0 | 1 | 4 | 20 | 65 | 166 | 312 | 505 | 745 | 1,035 |
| Total serious injuries avoided | | | | | | | | | | | | |
| Category | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 |
| Pedestrian | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bicycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Motorcycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 37 | 112 | 291 | 611 |
| Vehicles | 0 | 0 | 0 | 6 | 37 | 173 | 565 | 1,438 | 2,695 | 4,323 | 6,311 | 8,645 |
| Total | 0 | 0 | 0 | 6 | 37 | 173 | 565 | 1,444 | 2,732 | 4,435 | 6,602 | 9,257 |

*Table 27: Number of fatalities and serious injuries avoided – high scenario – 2030 to 2040.*

| LTE-V2X (PC5) - High | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Total fatalities avoided | | | | | | | | | | | |
| Category | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 |
| Pedestrian | 669 | 757 | 840 | 920 | 994 | 1,058 | 1,112 | 1,144 | 1,156 | 1,148 | 1,140 |
| Bicycles | 264 | 299 | 332 | 363 | 392 | 418 | 439 | 452 | 456 | 453 | 450 |
| Motorcycles | 80 | 122 | 170 | 224 | 283 | 345 | 408 | 466 | 518 | 560 | 602 |
| Vehicles | 1,377 | 1,733 | 2,125 | 2,551 | 2,989 | 3,407 | 3,788 | 4,042 | 4,159 | 4,132 | 4,107 |
| Total | 2,390 | 2,910 | 3,466 | 4,058 | 4,659 | 5,227 | 5,746 | 6,105 | 6,289 | 6,293 | 6,299 |
| Total serious injuries avoided | | | | | | | | | | | |
| Category | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 |
| Pedestrian | 8,684 | 9,823 | 10,902 | 11,938 | 12,897 | 13,729 | 14,427 | 14,850 | 15,005 | 14,898 | 14,793 |
| Bicycles | 5,382 | 6,088 | 6,757 | 7,399 | 7,993 | 8,509 | 8,942 | 9,204 | 9,300 | 9,234 | 9,169 |
| Motorcycles | 1,231 | 1,880 | 2,624 | 3,460 | 4,369 | 5,319 | 6,290 | 7,192 | 7,990 | 8,649 | 9,296 |
| Vehicles | 12,290 | 15,469 | 18,967 | 22,769 | 26,686 | 30,416 | 33,814 | 36,087 | 37,125 | 36,885 | 36,665 |
| Total | 27,586 | 33,260 | 39,250 | 45,566 | 51,946 | 57,973 | 63,472 | 67,334 | 69,421 | 69,665 | 69,923 |
| 802.11p - High | | | | | | | | | | | |
| Total fatalities avoided | | | | | | | | | | | |
| Category | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 |
| Pedestrian | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bicycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Motorcycles | 74 | 113 | 157 | 208 | 262 | 319 | 377 | 432 | 479 | 519 | 558 |
| Vehicles | 1,302 | 1,638 | 2,009 | 2,412 | 2,827 | 3,222 | 3,581 | 3,822 | 3,932 | 3,907 | 3,883 |
| Total | 1,376 | 1,751 | 2,166 | 2,619 | 3,089 | 3,541 | 3,959 | 4,254 | 4,412 | 4,426 | 4,441 |
| Total serious injuries avoided | | | | | | | | | | | |
| Category | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 |
| Pedestrian | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bicycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Motorcycles | 1,107 | 1,690 | 2,359 | 3,110 | 3,927 | 4,781 | 5,653 | 6,465 | 7,182 | 7,774 | 8,356 |
| Vehicles | 11,315 | 14,243 | 17,463 | 20,964 | 24,571 | 28,005 | 31,133 | 33,226 | 34,182 | 33,961 | 33,758 |
| Total | 12,422 | 15,932 | 19,822 | 24,074 | 28,498 | 32,786 | 36,786 | 39,691 | 41,364 | 41,734 | 42,114 |

*Table 28: Number of fatalities and serious injuries avoided – low scenario – 2018 to 2029.*

| LTE-V2X (PC5) - Low | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Total fatalities avoided | | | | | | | | | | | | |
| Category | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 |
| Pedestrian | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bicycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Motorcycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 5 | 12 | 24 |
| Vehicles | 0 | 0 | 0 | 1 | 4 | 15 | 40 | 83 | 147 | 239 | 364 | 527 |
| Total | 0 | 0 | 0 | 1 | 4 | 15 | 40 | 83 | 149 | 245 | 376 | 551 |
| Total serious injuries avoided | | | | | | | | | | | | |
| Category | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 |
| Pedestrian | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bicycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Motorcycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 28 | 83 | 189 | 368 |
| Vehicles | 0 | 0 | 0 | 7 | 39 | 135 | 358 | 738 | 1,315 | 2,136 | 3,250 | 4,709 |
| Total | 0 | 0 | 0 | 7 | 39 | 135 | 358 | 743 | 1,343 | 2,220 | 3,439 | 5,077 |
| 802.11p - Low | | | | | | | | | | | | |
| Total fatalities avoided | | | | | | | | | | | | |
| Category | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 |
| Pedestrian | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bicycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Motorcycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 3 | 6 |
| Vehicles | 0 | 0 | 0 | 0 | 1 | 3 | 7 | 17 | 35 | 65 | 113 | 190 |
| Total | 0 | 0 | 0 | 0 | 1 | 3 | 7 | 17 | 35 | 66 | 116 | 195 |
| Total serious injuries avoided | | | | | | | | | | | | |
| Category | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 |
| Pedestrian | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bicycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Motorcycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 8 | 20 | 42 | 87 |
| Vehicles | 0 | 0 | 1 | 3 | 9 | 23 | 60 | 144 | 300 | 563 | 983 | 1,648 |
| Total | 0 | 0 | 1 | 3 | 9 | 23 | 60 | 146 | 308 | 583 | 1,025 | 1,735 |

*Table 29: Number of fatalities and serious injuries avoided – low scenario – 2030 to 2040.*

| LTE-V2X (PC5) - Low | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Total fatalities avoided | | | | | | | | | | | |
| Category | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 |
| Pedestrian | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bicycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Motorcycles | 40 | 62 | 90 | 124 | 165 | 210 | 260 | 314 | 367 | 420 | 472 |
| Vehicles | 736 | 991 | 1,300 | 1,645 | 2,010 | 2,365 | 2,695 | 2,987 | 3,221 | 3,428 | 3,606 |
| Total | 776 | 1,053 | 1,389 | 1,769 | 2,175 | 2,575 | 2,955 | 3,300 | 3,588 | 3,847 | 4,078 |
| Total serious injuries avoided | | | | | | | | | | | |
| Category | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 |
| Pedestrian | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bicycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Motorcycles | 620 | 954 | 1,386 | 1,915 | 2,539 | 3,243 | 4,017 | 4,842 | 5,657 | 6,476 | 7,289 |
| Vehicles | 6,568 | 8,847 | 11,602 | 14,687 | 17,944 | 21,110 | 24,057 | 26,661 | 28,753 | 30,600 | 32,190 |
| Total | 7,188 | 9,801 | 12,987 | 16,602 | 20,483 | 24,353 | 28,074 | 31,503 | 34,410 | 37,075 | 39,479 |
| 802.11p - Low | | | | | | | | | | | |
| Total fatalities avoided | | | | | | | | | | | |
| Category | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 |
| Pedestrian | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bicycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Motorcycles | 11 | 20 | 34 | 52 | 76 | 107 | 147 | 192 | 238 | 285 | 332 |
| Vehicles | 308 | 479 | 697 | 954 | 1,231 | 1,534 | 1,858 | 2,192 | 2,516 | 2,816 | 3,092 |
| Total | 319 | 499 | 731 | 1,005 | 1,306 | 1,641 | 2,005 | 2,383 | 2,754 | 3,101 | 3,424 |
| Total serious injuries avoided | | | | | | | | | | | |
| Category | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 |
| Pedestrian | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bicycles | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Motorcycles | 170 | 305 | 502 | 773 | 1,133 | 1,607 | 2,206 | 2,869 | 3,565 | 4,272 | 4,972 |
| Vehicles | 2,673 | 4,160 | 6,063 | 8,291 | 10,698 | 13,335 | 16,147 | 19,054 | 21,868 | 24,480 | 26,881 |
| Total | 2,844 | 4,465 | 6,565 | 9,064 | 11,831 | 14,942 | 18,353 | 21,923 | 25,433 | 28,752 | 31,853 |

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