

# REDUCING FATALITIES IN ROAD CRASHES IN JAPAN, GERMANY, AND USA WITH V2X-ENHANCED-ADAS

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## ABSTRACT

### Objective

While Advanced Driver Assistance Systems (ADAS) improve safety, on-board sensors such as cameras, radar and lidar have limitations in preventing crashes: a) early recognition of non-line-of-sight (NLOS) vehicles and vulnerable road users (VRU: pedestrians, bicyclists, and motorcyclists) and b) early recognition of the intention of other road users. V2X technology can overcome this challenge.

Basic V2X use direct short-range communication between vehicles and provides only a gradual solution toward improving ADAS. First, the slow introduction rate of V2X results in a low likelihood of both vehicles being equipped with V2X and therefore in preventing a crash. Second, there are impediments to VRU participation in V2X communication, resulting in a lack of VRU protection in NLOS scenarios.

Collective Perception V2X using sensor data sharing can help to protect vehicles without V2X technology. Collective Perception V2X can also help to protect VRU by sharing information on road users that is collected by sensors in other vehicles or on intelligent infrastructure.

The first objective of this paper is to quantify how Basic V2X can address fatal crashes in conjunction with ADAS by improving situational awareness in non-line-of-sight scenarios, and by providing information on the intention of traffic participants in critical situations.

The second objective of this paper is to quantify how Collective Perception V2X can further boost the effective equipment rate in vehicles and protect VRU that are not otherwise protected by Basic V2X and ADAS.

### Method

Using crash statistics from Japan, Germany, and the US, we analyzed the share of fatal crashes between vehicles and VRU. Crash scenarios due to limitations of on-board sensors were identified to quantify the target population for V2X. Starting with the V2X introduction rates presumed by the US DOT NPRM [1], we modeled the effective V2X communication rates for vehicles and VRU over time, assuming that all vehicles were equipped with ADAS.

We analyzed the benefit of Basic V2X, in addition to conventional ADAS, in addressing vehicle-vs-vehicle and vehicle-vs-VRU crashes. We investigated whether Collective Perception V2X could increase the effective communication rate between vehicles. Additionally, we examined how Collective Perception V2X could help to detect VRU that are insufficiently addressed in NLOS circumstances. The analysis included intersections with potential intelligent infrastructure and roadways without infrastructure.

### Results

The following three fields-of-action of Basic V2X and Collective Perception V2X were identified, and the potential in addressing vehicle-vs-vehicle and vehicle-vs-VRU crashes, were quantified:

- Basic V2X raises the awareness of other equipped vehicles,
- Collective Perception V2X boosts the effective vehicle equipment rate,
- Collective Perception V2X protects VRU that are otherwise unprotected.

### Outlook

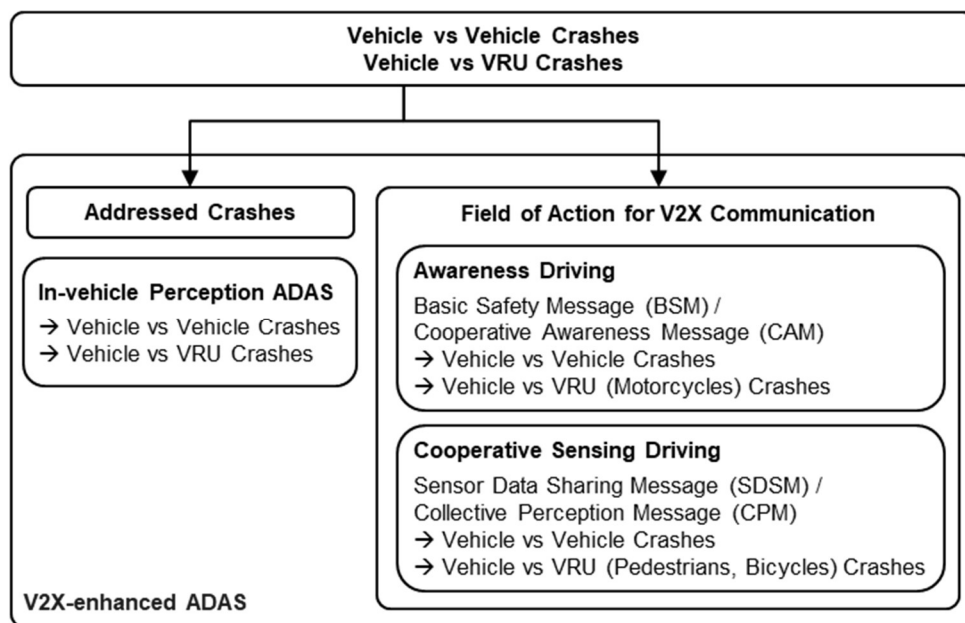
The results indicate that the combination of Basic V2X, Collective Perception V2X, and ADAS can be highly beneficial for road safety. It is therefore important to ensure sufficient and protected frequency spectrum in the 5.9 GHz band for basic and advanced V2X messages like BSM/CAM and SDSM/CPM. Subsequent research should focus on analyzing the potential of V2X for automatic emergency braking, including safety level considerations when utilizing over-the-air V2X data.

# 1. INTRODUCTION

Modern cars are equipped with Advanced Driver Assistance Systems (ADAS) that use on-board line-of-sight (LoS) sensors such as cameras, radar and lidar. They prevent or mitigate traffic crashes by controlling actuators for braking, accelerating, or steering. While ADAS are key for improving safety, they have limitations due to the nature of the LoS sensors to provide sufficiently early notifications. Other traffic participants may be obstructed or outside the coverage of the on-board sensor and therefore may not be detected. Also, the movement of other vehicles cannot easily be anticipated at the time of pedal or steering wheel actuation but perhaps only after such actuation has resulted in vehicle acceleration in any direction. In both cases, critical situations may not be detected in time to prevent an accident.

V2X technology aims at closing this gap and provides additional information about other vehicles, their movement and intent, as well as VRU. Thus, ADAS benefit from this additional information and further by earlier detection of non-light-of-sight vehicles and VRU, and by indications of the intention of other road users. Namely Basic V2X and Collective Perception V2X contribute relevant information to an V2X-enhanced ADAS.

Figure 1 shows how vehicle-vs-vehicle and vehicle-vs-VRU crashes are addressed by V2X-enhanced ADAS. V2X communication can extend the field of action in which a safety system can become active.



**Figure 1: V2X-enhanced ADAS addressing vehicle-vs-vehicle crashes and vehicle-vs-VRU crashes.**

This paper aims to answer the following research questions:

- To what extent does V2X-enhanced ADAS, that utilizes Basic V2X and Collective Perception V2X, address vehicle-vs-vehicle crashes?
- To what extent does V2X-enhanced ADAS, that utilizes Basic V2X and Collective Perception V2X, improve VRU safety?

These research questions will be discussed using accident data inflicting fatal injuries from Japan in 2021 [2], Germany in 2020 [3], [4] and the US in 2020 [5].

## 2. BASIC V2X AND COLLECTIVE PERCEPTION V2X

V2X communication utilizes different message types to exchange information between vehicles and with roadside units, including the position and movement of vehicles and VRU. Basic Safety Messages (BSM) are directly exchanged between vehicles that are equipped with V2X technology. Each vehicle transmits regular BSM providing its own status. As BSM are used in the US, the corresponding Cooperative Awareness Messages (CAM) with similar data contents are used in Europe.

Sensor Data Sharing Messages (SDSM) can provide information about vehicles that are not fitted with V2X technology or about VRU that do not participate in V2X communication. The equivalent Collective Perception Messages (CPM) are specified for Europe.

The goal of BSM/CAM and SDSM/CPM is to inform receiving vehicles on impending dangerous situations due to position, movement, or status of other vehicles and VRU.

Table 1 describes the relevant message types used in this analysis. The usage of message types is independent of the specific V2X radio communication technology (IEEE 802.11p / LTE-V2X / 5G NR-V2X / IEEE 802.11bd).

**Table 1: Definition of important V2X message types enabling different V2X applications.**

| V2X level                 | Message types | Classes of cooperation                            | Description and related technical standards   |
|---------------------------|---------------|---|---|
| Basic V2X                 | BSM/CAM       | Awareness Driving (Status Sharing)                | Basic Safety Messages (BSM) or Cooperative Awareness Messages (CAM) increase the awareness horizon by sharing the vehicle status (position, movement vector, vehicle class, wiper, and brake pedal status) and alert on impending dangerous situations.<br>SAE J2735, SAE J2945/1, ETSI EN 302 637-2.   |
| Collective Perception V2X | SDSM/CPM      | Cooperative Sensing Driving (Sensor Data Sharing) | Sensor Data Sharing Messages (SDSM) or Collective Perception Messages (CPM) provide information on detected objects (traffic participants, road objects) in the surroundings of a vehicle or road infrastructure by sharing the vehicle or VRU status (position, movement vector, object type).<br>SAE J3224, ETSI TS 103 324, ETSI TR 103 562. |

Figure 2 shows the functionality of Collective Perception V2X in addressing vehicle-vs-vehicle crashes and vehicle-vs-VRU crashes. If a vehicle is not equipped with V2X, it cannot communicate to other vehicles itself. However, third-party V2X-equipped vehicles can detect the non-equipped vehicle using their on-board sensors and transmit this detection to other V2X-capable traffic participants. VRU who do not participate in V2X communication themselves, can be detected by V2X-equipped vehicles and by roadside units, who in return can provide this information to other V2X participants. Thus, Collective Perception V2X can be thought of as “seeing through the eyes of others” to improve awareness of non-equipped vehicles and VRU.



**Figure 2: Left: Truck sends information to red vehicle regarding non-V2X-equipped white vehicle. Right: White vehicle sends information to red vehicle regarding NLOS VRU [6].**

Note that in the following analysis we model the Basic V2X communication rate over time using the example of BSM and the Collective Perception V2X communication rate over time using the example of SDSM. However identical results will be achieved using the corresponding message types CAM and CPM, respectively.

### 3. FATAL ROAD CRASHES

Traffic crashes in Japan, Germany, and the US are analyzed to quantify the field-of-action, in which V2X-enhanced ADAS can become effective. To allow for an overview of the total accident situation in each country, the fatal crashes are grouped into single-vehicle crashes and crashes that are caused in conflict situations between two participants. While the former are often due to loss of control, the latter are mostly caused by negligence or driver inattentiveness.

Figure 3 gives an overview of fatal crashes in Japan, Germany, and the US. The distribution significantly varies between the countries. Conflict crashes involving two cars are dominant in Germany and the US, being responsible for 16% and 25% of fatalities, respectively. Car crashes with pedestrians are of high relevance, especially in Japan where these account for 27% of traffic fatalities. In Germany and the US, they cause 9% and 13% of fatalities, respectively. In Japan 54 of traffic fatalities are caused in vehicle-vs-VRU crashes.

In the following, two different target populations are defined to show the potential of V2X-enhanced ADAS in addressing fatal crashes and particularly the additional benefit of Basic V2X and Collective Perception V2X: Vehicle-vs-vehicle crashes and vehicle-vs-VRU crashes.

Please note that no consideration has been given to the change of road traffic participation and thus to the distribution of accident participants and accident conflicts, due to Covid-related travel patterns and social circumstances.

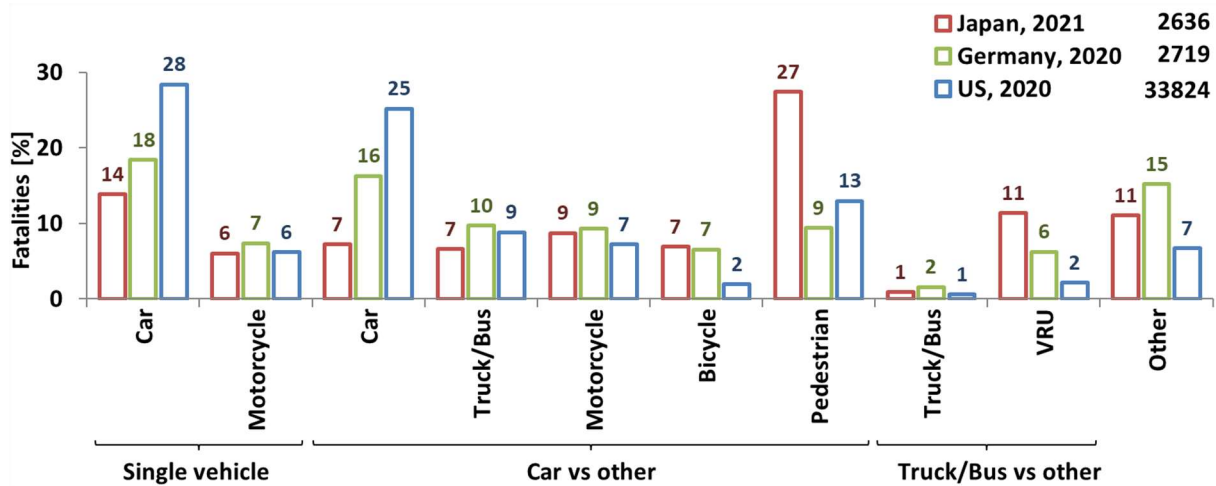


Figure 3: Traffic fatalities in Japan, Germany and the US.

The group of vehicle-vs-vehicle crashes split up into three combinations of conflicts between cars and trucks. The largest share are crashes between two cars, accounting for 186 fatalities in Japan, 442 in Germany and 9,773 in the US, in the respective years. The second largest group are crashes between cars and trucks, followed by crashes involving two trucks. It should be noted that busses are treated together with trucks in this analysis.

In all vehicle-vs-vehicle crashes, crossing/turning scenarios (39% in Germany) and oncoming scenarios (40% in Japan) are most relevant in causing fatalities. See Figure 4 for an overview of all fatal vehicle-vs-vehicles in the different countries.

Pedestrians are most vulnerable and make up the largest share of all fatalities in vehicle-vs-VRU crashes. In crashes with cars, 708 pedestrians were killed in Japan, 255 in Germany and 5,027 in the US, in the analyzed data years. Note that motorcycles are counted as VRU in this analysis. They represent the second most endangered group of VRU with 2,794 motorcyclists killed in the US alone in 2020. Bicycles are the third relevant group of endangered VRU in crashes with cars. The large number of 178 bicyclist fatalities in crashes with cars in Germany in 2020 correlates with the high bicycle usage in this country. Finally, trucks play a crucial role in fatal crashes with VRU.

The majority of vehicle-vs-VRU crashes occur in crossing and turning scenarios. These are scenarios with an ego vehicle going straight or turning at an intersection and the respective VRU crossing the path of the ego vehicle. Crossing/turning account for the highest share of fatal vehicle-vs-pedestrian crashes: 74% in Japan, 74% in Germany and 63% in the US. Crossing/turning crashes are equally relevant in car-vs-motorcycle crashes: 66% in Japan, 49% in Germany and 55% in the US. Within the group of car-vs-bicycle crashes, crossing/turning scenarios are significant in Japan and Germany with 69% and 80% of fatal crashes. A detailed analysis of car-vs-bicycle crashes including the relevant scenarios and pre-crash characteristics are described in [7]. Figure 5 shows the different shares of fatal vehicle-vs-VRU crashes.

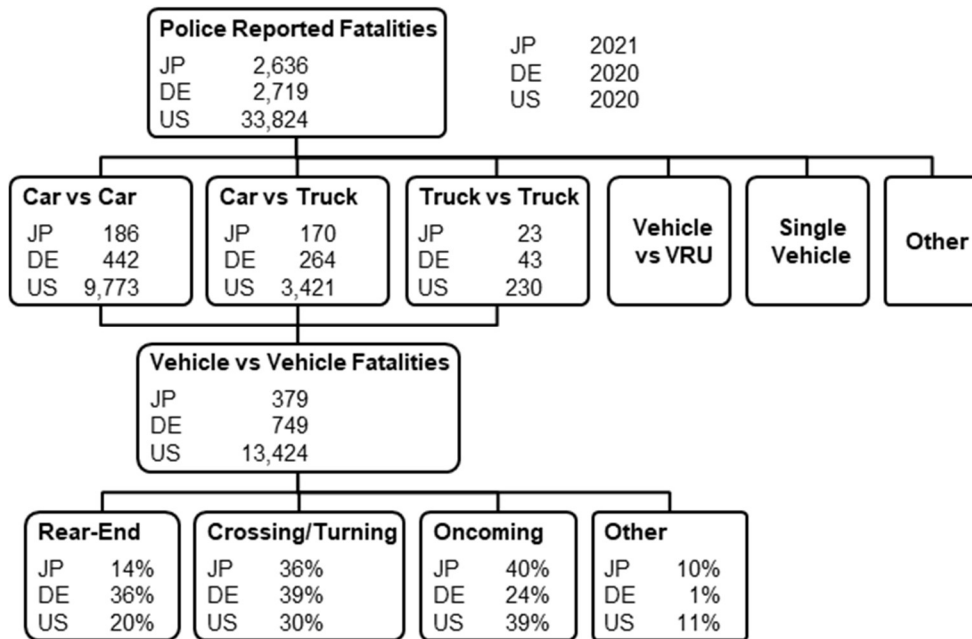


Figure 4: Fatalities in vehicle-vs-vehicle crashes in Japan, Germany and the US.

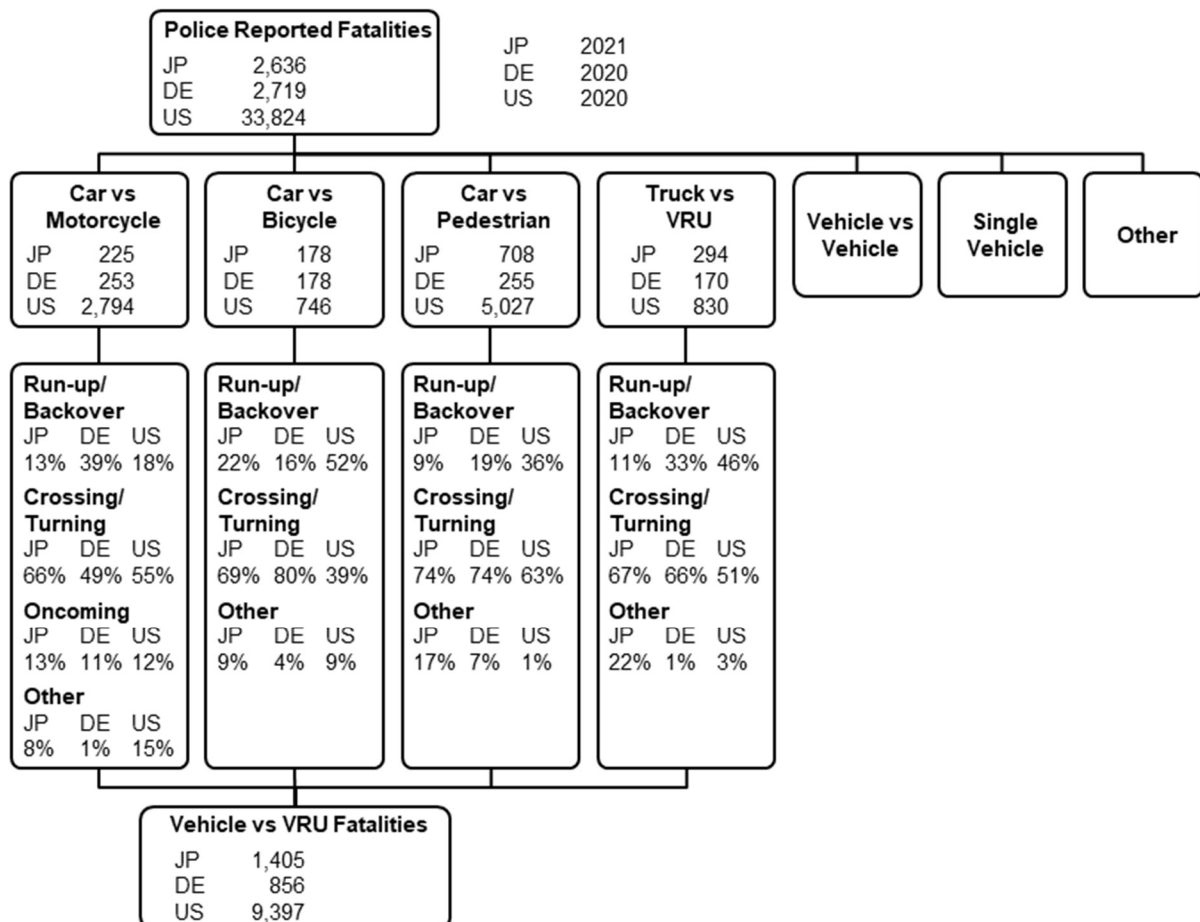


Figure 5: Fatalities in vehicle-vs-VRU crashes in Japan, Germany and the US.

Obstructed traffic participants that are in non-line-of-sight cannot be detected by ADAS onboard sensors. Other vehicles and VRU might be obstructed, due to stationary objects such as parked vehicles, or due to roadside structures such as buildings or trees.

The GIDAS pre-crash data PCM was analyzed to quantify view obstructions in vehicle-vs-vehicle and vehicle-vs-VRU crashes [8]. At time-to-collision  $TTC=2s$ , 32% of crossing cars, 30% of crossing motorcycles, 25% of

crossing bicycles, and 34% of crossing pedestrians are obstructed. At that time, typical Euro NCAP tests require the detection of crash targets [9]. Since GIDAS considers only stationary obstructions at the scene of the accidents, the real share of crashes with obstructions will be even higher. V2X technology can support by providing information about the obstructed vehicles or VRU. Figure 6 shows the share of stationary obstructed vehicles and VRU in crossing crashes from left and right.

The Euro NCAP project SECUR identified relevant participants, specific crash scenarios, and important environment conditions where V2X communication can support to improve vehicle safety [10].

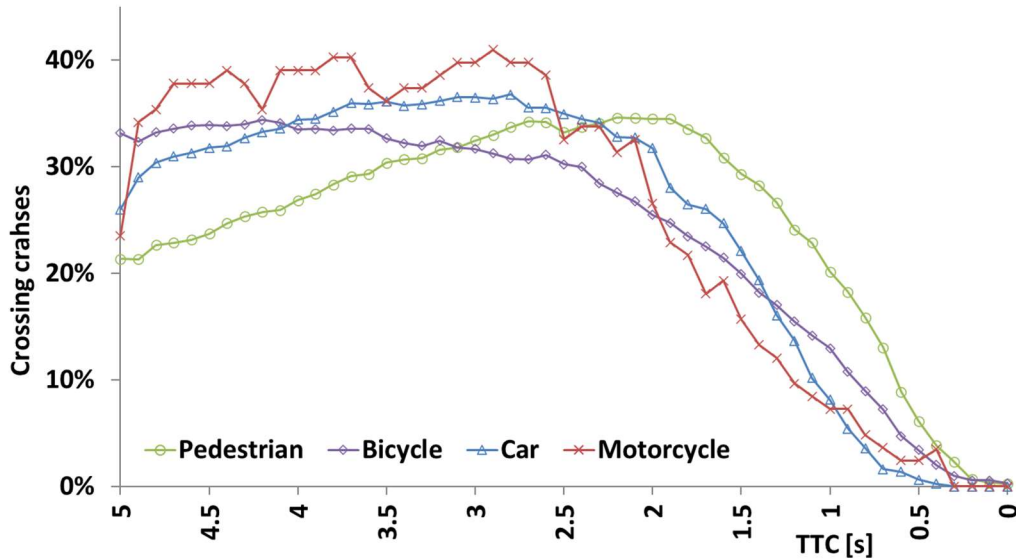


Figure 6: Share of stationary obstructions in crossing crashes (from left or right) with different objects.

ADAS predict the velocities of other objects to determine the likelihood that a crash is unavoidable and to activate automatic braking or steering. Depending on the viewpoint of the ego vehicle, crossing crashes can be considered as two individual scenarios, with crossing vehicles from different directions, left or right, [11]. Therefore, ADAS need to include the causer and the non-causer perspective of the crash, in case the other vehicles might not be equipped with a safety system.

If the ego vehicle is not causer of the crash, it typically moves at speeds of around 50 km/h, whereas the causing object vehicles travels at lower speeds. In 40% of crossing vehicle-vs-vehicles crashes, in which the opponent vehicle is causer, the object speeds are smaller than 20 km/h. However, slow crossing vehicles are difficult to judge by using on-board sensors and might be excluded from the ADAS coverage to avoid false-positive activations. Currently, also Euro NCAP covers crossing Global Vehicles Targets (GVT) at test speeds of 20 km/h and above only, [12]. V2X technology can support the detection of slow-moving crossing vehicles by providing the driver intention based on pedal actuation, and the actual vehicle dynamics measured by wheel sensors. Figure 7 shows the pre-crash speeds of ego vehicles and crossing vehicles, in case the crossing vehicle is crash causer.

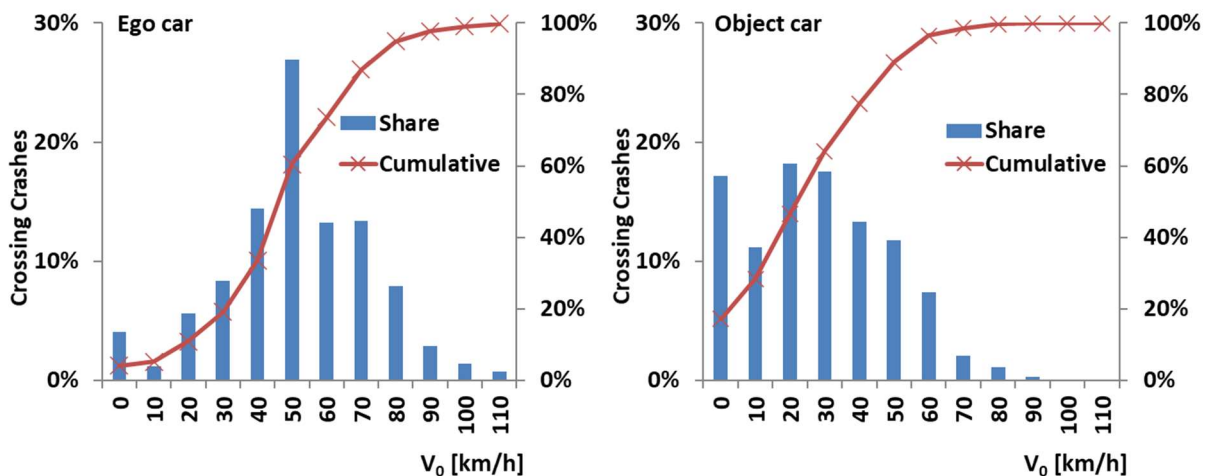


Figure 7: Pre-crash speeds in car-vs-car crossing crashes (from left or right) - if ego is non-causer.

#### 4. V2X TECHNOLOGY ADDRESSING VEHICLE-VS-VEHICLE CRASHES

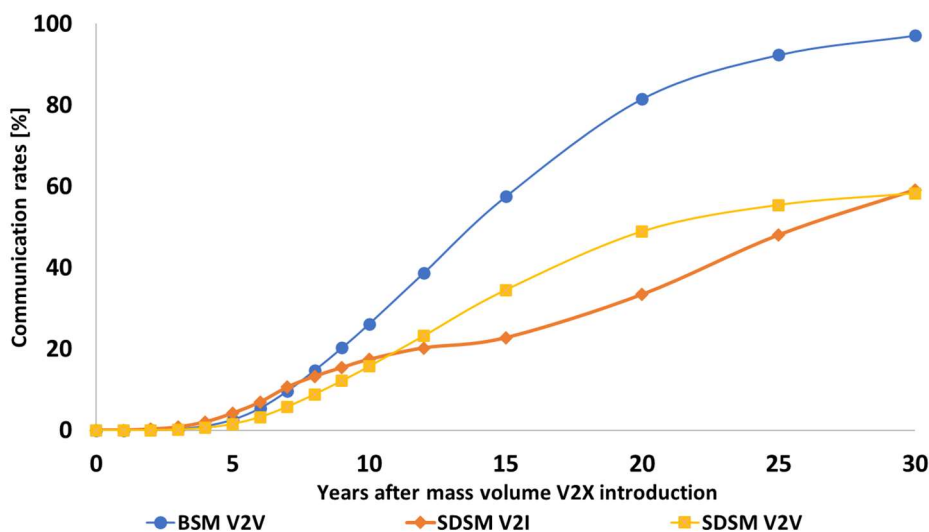
Effective V2X communication between two vehicles depends on overall vehicle equipment rates and increases over time beginning with the introduction of V2X technology. Basic V2X applying BSM, and Collective Perception V2X applying SDSM, can detect opponent vehicles in critical situations. Three communication paths between vehicles are possible:

- Basic V2X - using BSM V2V: The communication rate between two vehicles exchanging CAM, dependent on the average V2X equipment rate in vehicles.
- Collective Perception V2X - using SDSM V2I: Vehicles that are not equipped with V2X can be detected by roadside units in smart intersections using cameras or radar sensors. The roadside units then broadcast information regarding the vehicles via SDSM.
- Collective Perception V2X - using SDSM V2V: Vehicles can be detected by third-party vehicles which use their own on-board sensors, and those third-party vehicles then can broadcast this information via SDSM. The effective communication rate depends on the existence of a third-party vehicle and whether it detects the target vehicle.

Table 2 explains how the different individual communication rates for vehicle-to-vehicle communication are calculated. See also in [13] for more details.

**Table 2: V2X communication rates relevant for vehicle-vs-vehicle communication.**

| Individual communication rates |   | Description   |
|--------------------------------|---|---|
| BSM V2V                        | $C_{BSM\ V2V} = ER_{Veh} * ER_{Veh}$        | Two vehicles communicating via BSM.<br>Assume vehicle equipment rate $ER_{Veh}$ as in mass V2X introduction according to NHTSA NPRM [1].  |
| SDSM V2I                       | $C_{SDSM\ V2I} = ER_{Veh} * ER_{Int} * G$   | Vehicle and smart intersection communicating via SDSM and sharing information about a non-equipped vehicle.<br>Assume that intersection equipment rate $ER_{Int}$ is increasing along with $ER_{Veh}$ . to max 60% each in 30 years.<br>Assume that intersections with the highest traffic throughput will be equipped more quickly than other intersections: $G = 3.5$ in year 6 and 1 in year 15.   |
| SDSM V2V                       | $C_{SDSM\ V2V} = ER_{Veh} * ER_{Veh} * 0.6$ | Two vehicles communicating via SDSM and sharing information about a non-equipped vehicle.<br>Assume the likelihood of a second vehicle being present and detecting the non-equipped vehicle is 0.6.<br>Note: The non-equipped vehicle is not a factor for calculating the communication rate, because the detection and communication rates for this calculation applies equally for detecting V2X-equipped vehicles and non-V2X-equipped vehicles. |



**Figure 8: Communication rates for vehicle awareness, using BSM and SDSM.**

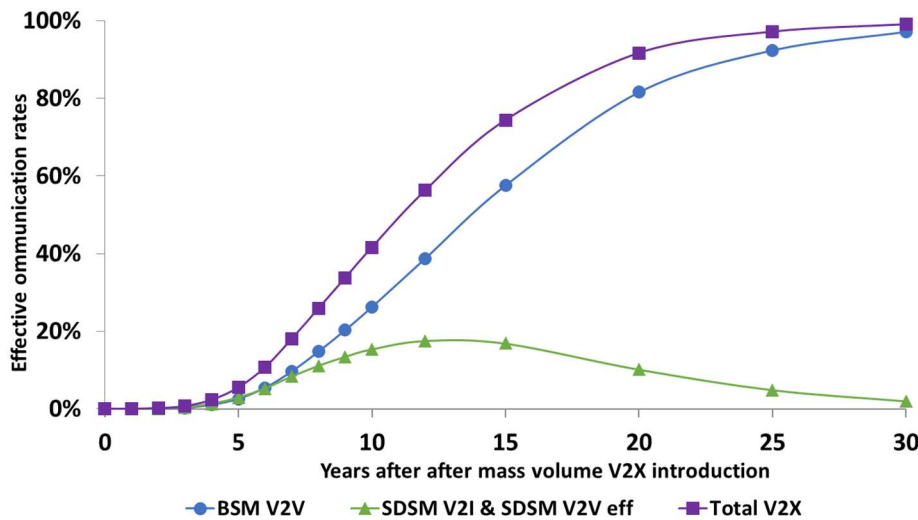
Figure 8 shows the three individual vehicle-to-vehicle communication rates over time, as calculated according to the formulas in Table 2. Each can increase the awareness of other vehicles in critical situations and thus address the same target population of vehicle-vs-vehicle crashes. The SDSM V2I communication rate grows more quickly in the early years due to the assumed higher installation rate of smart intersections. SDSM V2I has a larger effect than SDSM V2V up to year 10. Note that this does not equate to the actual number of crashes prevented which depends on how effectively a safety system would act on this information.

The different V2X communication paths are not mutually exclusive and sometimes provide vehicle awareness in the very same critical situation. The individual communication rates are therefore applied sequentially when calculating the individual effective shares in the V2X communication. Table 3 explains the formulas for calculating the effective SDSM communication rates, that apply on top of BSM communication, for vehicle-vs-vehicle communication, inside and outside of smart intersections. Here the following order introducing V2X technology is assumed: BSM, SDSM inside intersections, SDSM outside intersections.

**Table 3: Effective SDSM communication rates for vehicle-vs-vehicle communication.**

| Effective communication rates |  | Description  |
|-------------------------------|--|--|
| Inside intersections          | $C_{SDSM\ V2I\ eff} = C_{BSM\ V2V} \cup C_{SDSM\ V2I} - C_{BSM\ V2V}$                                      | Vehicle and smart intersection communicating via SDSM and sharing information about a non-equipped vehicle. Additional effect on top of BSM communication. Applies to share of intersection crashes.   |
|                               | $C_{CPM\ V2V\ eff} = C_{BSM\ V2V} \cup C_{SDSM\ V2I} \cup C_{SDSM\ V2V} - C_{BSM\ V2V} \cup C_{SDSM\ V2I}$ | Two vehicles communicating via SDSM and sharing information about a non-equipped vehicle. Additional effect on top of only BSM communication and on top of only SDSM vehicle and smart intersection communication. Applies to share of intersection crashes. |
| Outside intersections         | $C_{SDMS\ V2V\ eff} = C_{BSM\ V2V} \cup C_{SDMS\ V2V} - C_{SDMS\ V2V}$                                     | Two vehicles communicating via SDSM and sharing information on non-equipped vehicle. Additional effect on top of BSM communication. Applies to share of non-intersection crashes.  |

The total effective SDSM communication rate is calculated by summing up  $C_{SDMS\ V2I\ eff}$  and  $C_{SDMS\ V2V\ eff}$ , for inside and outside intersections. The calculation assumes a 35% share of vehicle-vs-vehicle crashes at intersections as analyzed for the US. The total effective SDSM communication rate peaks at around year 12 after market introduction. The additional benefit of SDSM communication on top of BSM communication is shown in Figure 9. It should be noted that the delta additional benefit of SDSM is non-zero across all 30 years under study, and is expected to provide positive, crash-reducing benefit. SDSM can therefore boost the effective V2X vehicle equipment rate, and thus accelerate the introduction of V2X technology.



**Figure 9: Effective vehicle-vs-vehicle communication: SDSM in addition to BSM.**



## 5. V2X-ENHANCED ADAS ADDRESSING VEHICLE-VS-VEHICLE CRASHES

The effectiveness of ADAS using on-board sensors, in addressing vehicle-vs-vehicle crashes, is limited in non-line-of-sight situations or where the intention of the other vehicle is unclear. State-of-the-art ADAS, particularly by using emergency braking (AEBS), can prevent around 50% of vehicle-vs-vehicle crashes, [14], [15], [16]. This assumes 100% ADAS market penetration. It should be noted that although 100% ADAS market penetration was assumed for these calculations, it should be understood that not every vehicle on the road is equipped with ADAS today. Rather, as of 2021, more than half of all new vehicles sold in the US, Japan, and Europe were equipped with some type of ADAS, and by 2030, it has been forecast that about 50% of all cars on the road globally (as of 2020, there were more than 1 billion cars on the road) will be equipped with ADAS [17]. BSM and SDSM can help to address these crashes by raising awareness of other vehicles and their intention. The conventional ADAS and the discussed V2X communication paths need to be considered as complementary to calculate the total number of crashes addressed, [10], [18].

Figure 10: shows the method of calculating the total number of vehicle-vs-vehicle crashes addressed by ADAS and by the different V2X communication paths. The addressed shares of the different technologies are deducted subsequently from the total number of crashes, in the order: ADAS, BSM, SDSM inside intersections, SDSM outside intersections. This order is according to the expected maturity and deployment of the different systems. The remaining number of crashes cannot be addressed by the discussed technologies. The given example shows the numbers in year 15 after V2X mass introduction.

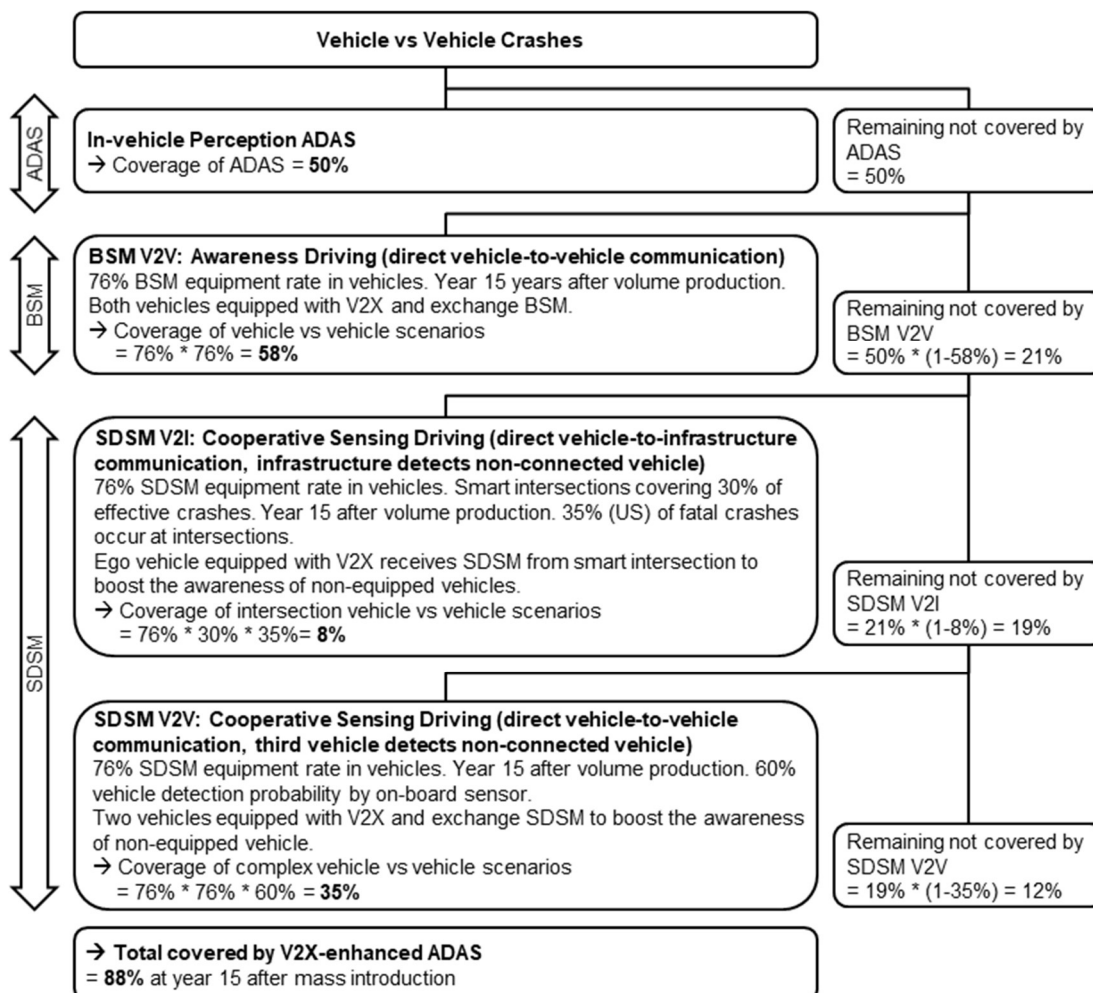
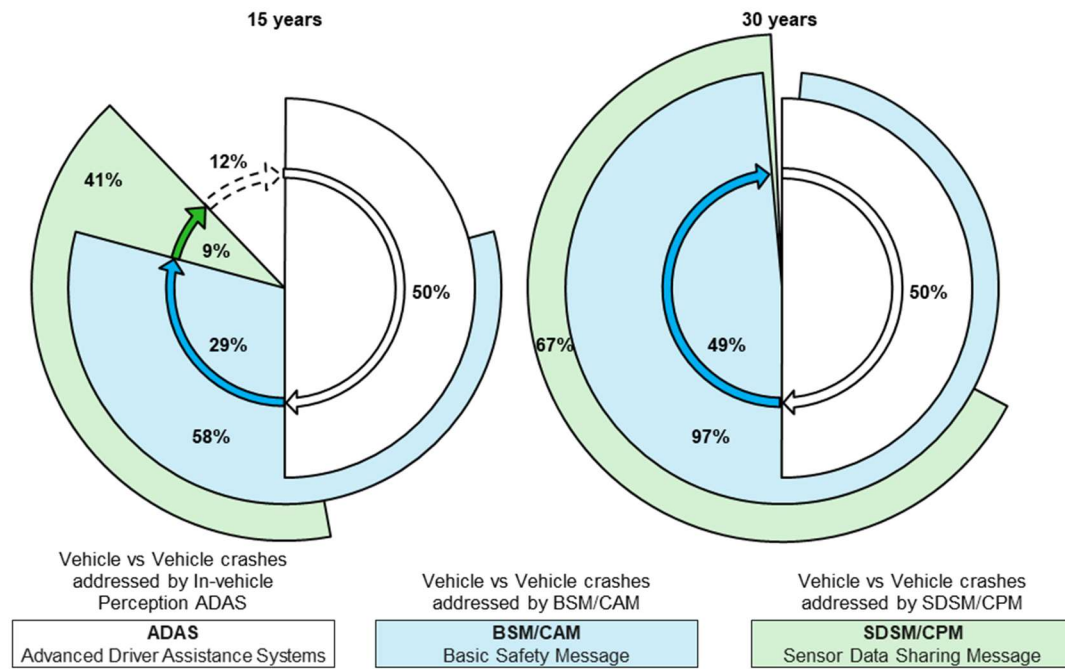


Figure 10: Complementary pairing of ADAS and V2X in addressing vehicle-vs-vehicle in year 15.

Figure 11 provides a different visualization of the overlapping fields-of-action addressed by the different technologies. Note that this assumes that the share of crashes addressed by ADAS is constant over time due to continuing use of line-of-sight sensors. In year 15 after V2X mass introduction a total of 88% of vehicle-vs-vehicle crashes are addressed by V2X-enhanced ADAS. At year 30 this number increases to 98%. As the share of BSM is growing over time, they cover almost the complete number of vehicle-vs-vehicle crashes at year 30. The relevance of SDSM in addressing vehicle-vs-vehicle crashes is mainly in early years to accelerate the safety

benefits of V2X. Note that this describes the set of crashes addressed by the system and not how effectively such crashes can be prevented or mitigated.



**Figure 11: Fields-of-action of V2X-enhanced ADAS addressing vehicle vs vehicle crashes. At year 15 and year 30 of introduction.**

The following benefits of adding Basic V2X and Collective Perception V2X to create V2X-enhanced ADAS, for addressing vehicle-vs-vehicle crashes, have been shown:

- Basic V2X, in addition to ADAS, can address relevant vehicle-vs-vehicle crashes by raising the awareness of other traffic participants in non-line-of-sight situations, and by providing information on the intention of traffic participants in critical situations.
- Collective Perception V2X, when combined with ADAS and Basic V2X, can accelerate the safety benefits of V2X technology by addressing an increased number of vehicle-vs-vehicle crashes, essentially by boosting the effective communication rate between vehicles over time.

The total numbers of vehicle-vs-vehicle fatalities addressed by the different technologies, in year 6, year 15 and year 30 in the different countries, are shown in Table 4. Additionally, it shows cumulative benefits up to the respective years.

**Table 4: Vehicle-vs-vehicle fatalities addressed by V2X-enhanced ADAS.**

|    |         | ADAS     | Basic V2X on top of ADAS<br>(not already covered by ADAS) |            | Collective Perception V2X on top of ADAS<br>and Basic V2X<br>(not already covered by ADAS or Basic V2X) |            |
|----|---------|----------|---|------------|---|------------|
|    |         | per year | per year  | cumulative | per year  | cumulative |
| JP | Year 6  | 190      | 10  | 20         | 10  | 15         |
|    | Year 15 | 190      | 100   | 330        | 30  | 160        |
|    | Year 30 | 190      | 180   | 850        | 5   | 200        |
| DE | Year 6  | 370      | 20  | 35         | 20  | 35         |
|    | Year 15 | 370      | 200   | 660        | 60  | 330        |
|    | Year 30 | 370      | 350   | 1 600      | 10  | 400        |
| US | Year 6  | 6 700    | 350   | 600        | 350   | 670        |
|    | Year 15 | 6 700    | 3 800   | 11 800     | 1 100   | 6 200      |
|    | Year 30 | 6 700    | 6 500   | 30 000     | 120   | 7 300      |

## 6. V2X TECHNOLOGY ADDRESSING VEHICLE-VS-VRU CRASHES

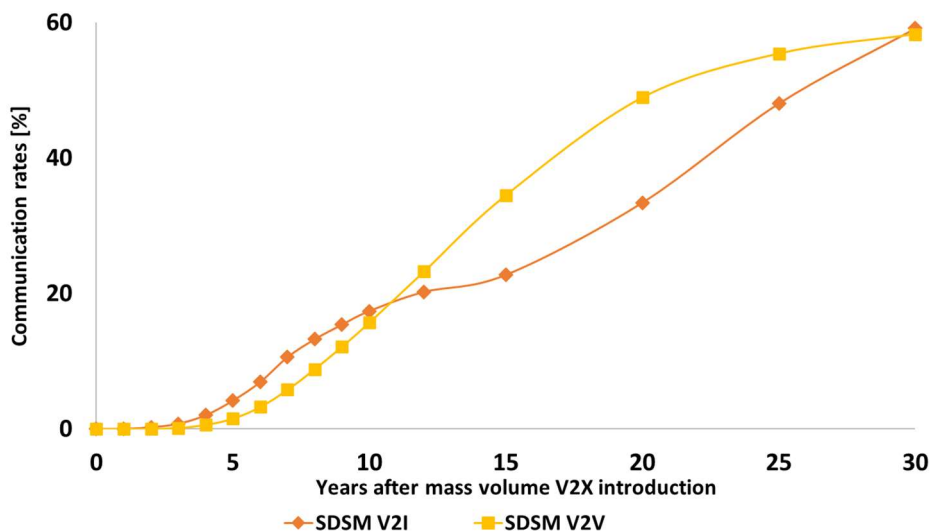
In the foreseeable future, VRU are highly unlikely to communicate via BSM due to a combination of factors including voluntary app installation and usage rates, no means to mandate that a smart device be carried by every VRU at all times, positioning accuracy, power consumption, and other factors. Therefore, VRU can best be addressed by Collective Perception V2X using infrastructure- and vehicle-oriented communication. An exception are motorcycles that can readily be fitted with V2X technology. The majority of VRU could therefore only be detected indirectly using vehicle and infrastructure sensors with SDSM communication. The communication paths for detecting VRU are as follows:

- Basic V2X - using BSM V2V: Direct vehicle-vs-VRU communication. Applies for motorcycles only. Other VRU cannot directly participate in V2X communication.
- Collective Perception V2X - using SDSM V2I: VRU can be detected by roadside units in smart intersections using cameras or radar sensors. The roadside units could then broadcast the relevant information about the VRU via SDSM.
- Collective Perception V2X - using SDSM V2V: VRU can be detected by third-party vehicles, using the third-party vehicles' own on-board sensors, which could transmit this information using SDSM. The communication rate depends on the existence of a third-party vehicle and whether it detects the VRU.

Table 5 shows the different individual communication rates for VRU awareness detection. The formulas correspond to those in vehicle-vs-vehicle communication because the sensor-based mechanisms of SDSM in increasing the awareness of non-V2X-equipped vehicles and of VRU are identical. See also in [13].

**Table 5: V2X communication rates relevant for vehicle-vs-VRU communication.**

| Individual communication rates |  | Description  |
|--------------------------------|--|--|
| BSM V2V                        | $C_{BSM V2V} = ER_{Veh} * ER_{Veh}$        | For detecting motorcycles only.<br>Note: VRU (except for motorcycles) cannot participate in SDSM communication.  |
| SDSM V2I                       | $C_{SDSM V2I} = ER_{Veh} * ER_{Int} * G$   | Vehicle and smart intersection communicating via SDSM and sharing information on VRU.<br>Assume that intersection equipment rate $ER_{Int}$ is increasing over time along with $ER_{Veh}$ . to max 60%.<br>Assume that intersections with highest traffic throughput will be equipped more quickly than other intersections: $G = 3.5$ in year 6 and 1 in year 15. |
| SDSM V2V                       | $C_{SDSM V2V} = ER_{Veh} * ER_{Veh} * 0.6$ | Two vehicles communicating via SDSM and sharing information on VRU.<br>Assume the likelihood of a second vehicle being present and detecting a non-equipped vehicle is 0.6.  |



**Figure 12: Communication rates for VRU awareness, using SDSM.**

Figure 12 depicts the run-up curves for VRU awareness using SDSM communication as calculated according to Table 5, not including BSM communication that can address motorcycles. Both communication paths address the

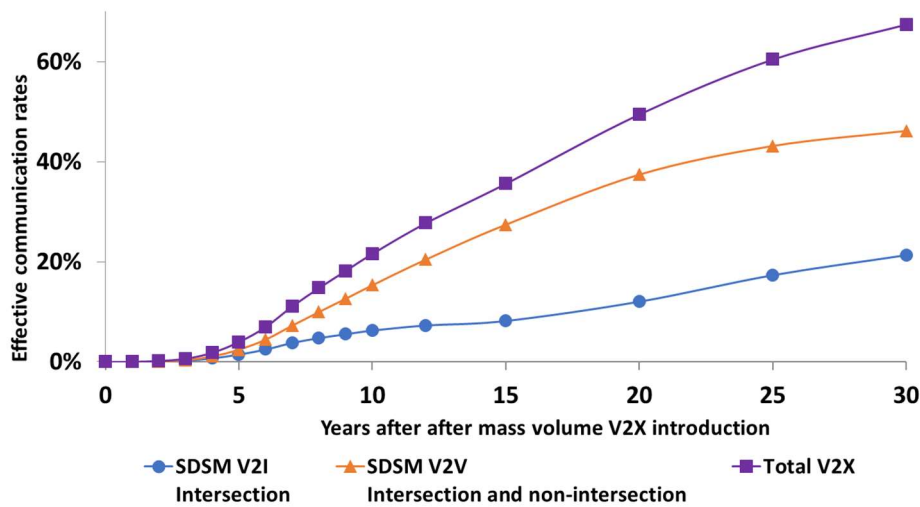
same target population of vehicle-vs-VRU crashes. The SDSM V2I communication rate grows more quickly in the early years due to the assumed higher installation rate of smart intersections. SDSM V2I has a larger effect than SDSM V2V up to year 10. Note that this only shows the share of addressed crashes, not the actual prevented crashes, as those depend on the effectiveness of the applied safety function.

The SDSM communication paths for detecting VRU are not mutually exclusive, because they address the same target population of vehicle-vs-VRU crashes. Therefore, the effective communication rates are calculated by deducting the area where another communication path has already been effective. The following order of calculating the effective communication rates is assumed, according to the expected introduction of SDSM: SDSM inside intersections, SDSM outside intersections. Table 6 describes the formulas to calculate the effective SDSM communication rates for vehicle-vs-VRU communication.

**Table 6: Effective SDSM communication rates for vehicle-vs-VRU communication.**

| Effective communication rates |   | Description   |
|-------------------------------|---|---|
| Inside intersections          | $C_{SDSM\ V2I\ eff} = C_{SDSM\ V2I}$                                    | Vehicle and smart intersection communicating via SDSM and sharing information about VRU.<br>Applies to share of intersection crashes.   |
|                               | $C_{SDSM\ V2V\ eff} = C_{SDSM\ V2I} \cup C_{SDSM\ V2V} - C_{SDSM\ V2I}$ | Two vehicles communicating via SDSM and sharing information about VRU.<br>Additional effect on top of BSM communication and on top of SDSM smart intersection communication.<br>Applies to share of intersection crashes. |
| Outside intersections         | $C_{SDSM\ V2V\ eff} = C_{BSM\ V2V}$                                     | Two vehicles communicating via SDSM and sharing information on VRU.<br>Applies to share of non-intersection crashes.  |

The total effective V2X communication rate, not including BSM communication that can address motorcycles, is calculated by adding  $C_{SDSM\ V2I\ eff}$  and  $C_{SDSM\ V2V\ eff}$ , for inside and outside intersections. The calculation assumes that 36% of vehicle-vs-VRU crashes occur inside intersections as analyzed for the US. The total V2X communication rate increases over time to cover 66% of VRU in year 30 after market introduction. SDSM V2I communication is effective inside intersections whereas SDSM V2V communication is effective inside and outside intersections. SDSM V2I between vehicles and smart intersection plays an important role in addressing vehicle-vs-VRU crashes and provides 6% effective communication rate at year 10 growing to 21% in year 30. Figure 13 shows the SDSM V2I and SDSM V2V communication rates and the total V2X communication rate for vehicle-vs-VRU communication.



**Figure 13: Effective vehicle-vs-VRU communication: SDSM V2V in addition to SDSM V2I.**

## 7. V2X-ENHANCED ADAS ADDRESSING VEHICLE-VS-VRU CRASHES

ADAS using on-board sensors often have limits in detecting VRU that are obstructed by vehicles or roadside structures and are therefore non-line-of-sight. ADAS including emergency braking (VRU-AEBS) functions can prevent around 55% of vehicle-vs-VRU crashes, [19], [20], [15]. Detailed accident scenarios with pedestrians and bicycles, in which conventional ADAS might not activate or might only mitigate, are also identified in [10], [18]. SDSM communication can, however, provide an additional input to the V2X-enhanced ADAS and help to raise awareness of VRU that are otherwise unprotected. Both ADAS using on-board sensors and V2X with SDSM communication complement one another to increase the total number of addressed vehicle-vs-VRU crashes.

In Figure 14, a method is described to derive the total number of addressed vehicle-vs-VRU crashes. Note that motorcycles are considered as VRU in this analysis, and thus are shown as participating in BSM communication. The benefit of BSM communication in addressing vehicle-vs-VRU crashes, however, only applies to the share of motorcycles within all VRU crashes. The following order is used to calculate the total number of addressed crashes: ADAS, BSM (for motorcycles only), SDSM inside intersections, SDSM outside intersections. All numbers are based on year 15 after V2X mass introduction.

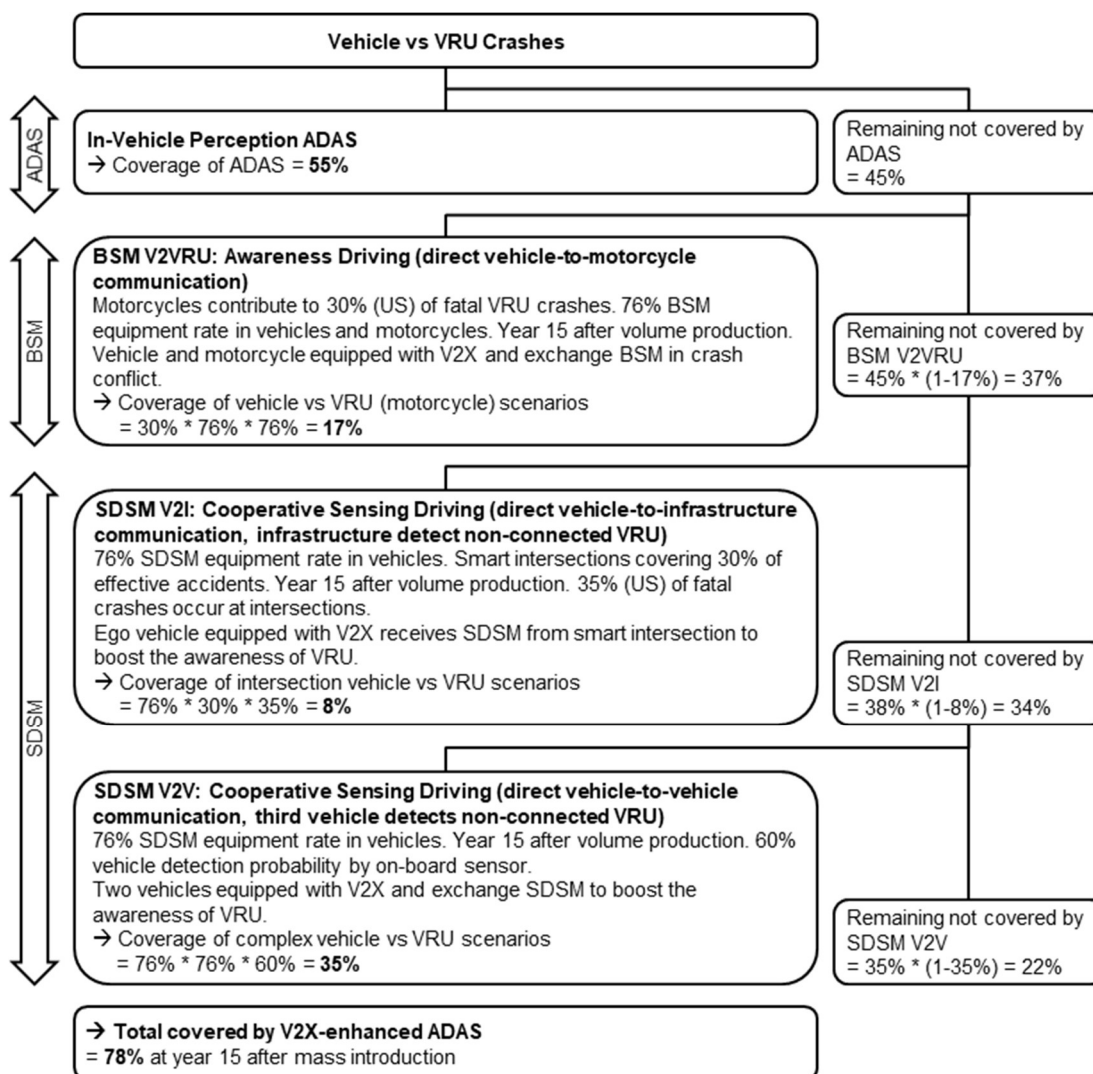
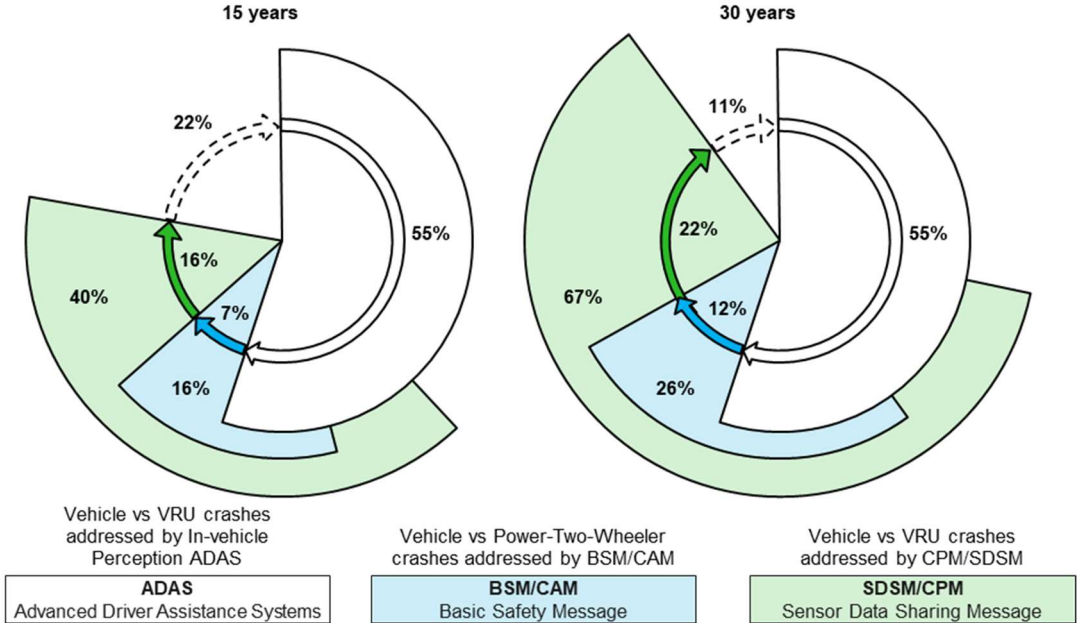


Figure 14: Complementary pairing of ADAS and V2X in addressing vehicle-vs-VRU crashes in year 15.

A visualization of the overlapping fields-of-action that are addressed by V2X-enhanced ADAS is shown in Figure 15. In year 15 after V2X mass introduction, 78% of vehicle-vs-VRU crashes are addressed, increasing to 89% in year 30. Direct communication via BSM plays a relatively small role in addressing vehicle-vs-VRU crashes, as V2X technology can only be added to motorcycles and not easily to pedestrians or bicycles. It should be emphasized that SDSM communication can play a crucial role in addressing vehicle-vs-VRU crashes. Roadside units in smart intersections can detect VRU and broadcast SDSM to raise awareness of VRU in critical situations in which the VRU might be obstructed. Outside of intersections, SDSM can be sent by vehicles that detect VRU

using their on-board sensors to inform other vehicles. SDSM can help close the gap in VRU protection in difficult non-line-of-sight situations that cannot be addressed by conventional ADAS. Note that the areas shown describe the share of vehicle-vs-VRU crashes that can be addressed by V2X-enhanced ADAS, without determining whether such crashes are prevented or mitigated which would be a factor of the action taken upon receipt of the information.



**Figure 15: Fields-of-action of V2X-enhanced ADAS addressing vehicle vs VRU crashes. At year 15 and year 30 after introduction.**

The following benefits of adding Basic V2X and Collective Perception V2X to create V2X-enhanced ADAS, for addressing vehicle-vs-VRU crashes, have been shown:

- Basic V2X, in addition to ADAS, can address vehicle-vs-motorcycle crashes by improving awareness in critical situations where the motorcycle is in non-line-of-sight.
- Collective Perception V2X, in addition to ADAS, can protect VRU in non-line-of-sight situations by improving awareness of NLOS VRU in critical situations.

Table 7 shows the number of vehicle-vs-VRU fatalities addressed by the different technologies, in year 6, year 15 and year 30 in the different countries and the cumulative benefits up to the respective years.

**Table 7: Vehicle-vs-VRU fatalities addressed V2X-enhanced ADAS.**

|    |         | ADAS     | Basic V2X on top of ADAS<br>(not already covered by ADAS)<br>(Motorcycles only) |            | Collective Perception V2X on top of ADAS<br>(not already covered by ADAS)<br>(all VRU) |            |
|----|---------|----------|---|------------|--|------------|
|    |         | per year | per year  | cumulative | per year   | cumulative |
| JP | Year 6  | 770      | 5   | 10         | 40   | 70         |
|    | Year 15 | 770      | 50  | 180        | 230  | 870        |
|    | Year 30 | 770      | 100   | 450        | 360  | 1 900      |
| DE | Year 6  | 470      | 5   | 10         | 20   | 40         |
|    | Year 15 | 470      | 65  | 200        | 120  | 500        |
|    | Year 30 | 470      | 110   | 500        | 180  | 1 000      |
| US | Year 6  | 5 100    | 60  | 110        | 230  | 440        |
|    | Year 15 | 5 100    | 700   | 2 200      | 1 400  | 5 300      |
|    | Year 30 | 5 100    | 1 200   | 5 600      | 2 000  | 11 000     |

## 8. CONCLUSION

The effective V2X communication rates for vehicles and VRU were modelled, when utilizing different V2X technologies, Figure 9 and Figure 13:

- Basic V2X - using BSM/CAM: Status sharing by direct short-range communication between vehicles.
- Collective Perception V2X - using SDSM/CPM: Sensor data sharing by short-range communication to detect vehicles without V2X technology and to detect VRU.

The benefit of Basic V2X and Collective Perception V2X in conjunction with ADAS, was shown. Three fields-of-action to address vehicle-vs-vehicle and vehicle-vs-VRU crashes were identified, Figure 11 and Figure 15:

- Basic V2X raises the awareness of other equipped vehicles,
- Collective Perception V2X boosts the effective vehicle equipment rate,
- Collective Perception V2X protects VRU that are otherwise unprotected.

The total crash reduction potential of V2X-enhanced ADAS, as a combination of Basic V2X, Collective Perception V2X and ADAS, was quantified, Figure 11 and Figure 15:

- Vehicle-vs-vehicle crashes addressed: 88% in year 15 and 98% in year 30 after V2X introduction.
- Vehicle-vs-VRU crashes addressed: 78% in year 15 and 89% in year 30 after V2X introduction.

The crash reduction potential of Collective Perception V2X in addition to Basic V2X was identified. Over the first six years after V2X introduction the cumulative additional field-of-action was quantified, Table 8:

- Collective Perception V2X doubles the vehicle-vs-vehicle crashes addressed by V2X technology  
US example: 600 fatalities by Basic V2X + 670 fatalities by Collective Perception V2X,
- Collective Perception V2X quintuples the vehicle-vs-VRU crashes addressed by V2X technology  
US example: 110 fatalities by Basic V2X + 440 fatalities by Collective Perception V2X.

The advantage of smart intersections for Collective Perception V2X to address vehicle-vs-VRU crashes was shown, Figure 13:

- Collective Perception V2I (vehicle-to-infrastructure) covers 6% of VRU in year 10 after V2X introduction,
- Collective Perception V2I (vehicle-to-infrastructure) covers 21% of VRU in year 30 after V2X introduction.

Since V2X enhanced-ADAS, namely Basic V2X, Collective Perception V2X in conjunction with ADAS, are shown to be highly beneficial for road safety of all traffic participants, it is important to ensure sufficient and protected frequency spectrum in the 5.9 GHz band for direct short-range V2X communication.

Table 8 shows the number of crash fatalities, cumulatively addressed by Basic V2X and Collective Perception V2X in the different countries, for year 6, year 15 and year 30 after start of V2X mass deployment.

**Table 8: Crash fatalities addressed by V2X in addition to ADAS.**

|    |         | Vehicle-vs-vehicle               |  | Vehicle-vs-VRU                             |  | Total crashes addressed by V2X |
|----|---------|----------------------------------|--|--|--|--------------------------------|
|    |         | Basic V2X on top of ADAS         | Collective Perception V2X on top of ADAS and Basic V2X | Basic V2X on top of ADAS (Motorcycle only) | Collective Perception V2X on top of ADAS (all VRU) |                                |
|    |         | cumulative until respective year |  |  |  |                                |
| JP | Year 6  | 20                               | 15   | 10   | 70   | 115                            |
|    | Year 15 | 330                              | 160  | 180  | 870  | 1 540                          |
|    | Year 30 | 850                              | 200  | 450  | 1 900  | 3 400                          |
| DE | Year 6  | 35                               | 35   | 10   | 40   | 120                            |
|    | Year 15 | 660                              | 330  | 200  | 500  | 1 690                          |
|    | Year 30 | 1 600                            | 400  | 500  | 1 000  | 3 500                          |
| US | Year 6  | 600                              | 670  | 110  | 440  | 1 820                          |
|    | Year 15 | 11 800                           | 6 200  | 2 200                                      | 5300   | 25 500                         |
|    | Year 30 | 30 000                           | 7 300  | 5 600                                      | 11 000   | 53 900                         |

This paper quantifies crash fatalities addressed by V2X-enhanced ADAS. However, the number of injured persons in road crashes is much higher: 100 times in Japan, 120 times in Germany and 60 times in the US.

Note that the actual number of prevented or mitigated crashes depends on how effectively safety systems will react on the V2X information by driver warning or automatic intervention.

## 9. REFERENCES

- [1] US Department of Transportation, National Highway Traffic Safety Administration, *Docket No, NHTSA–2016–0126*, 2017.
- [2] ITARDA (Institute for Traffic Accident Research and Data Analysis), *National Road Crash Data for Japan*, Data Year 2021.
- [3] GIDAS (German In-Depth Accident Data), *Road Crash Data Sample*, Data Years 2005-2022.
- [4] DESTATIS (German Federal Statistical Office), *Special Evaluation of National Road Crash Statistics on behalf of Continental*, Data Year 2020.
- [5] FARS (Fatality Analysis Reporting System), *National Road Crash Data for the USA*, NHTSA, Data Year 2020.
- [6] CAR 2 CAR Communication Consortium, *Graphics*.
- [7] N. Puller, G. Lucas, A. Leschke, O. Maier, J. Mönnich und V. Rocco, „The "Typical" Car-Cyclist Collision Under the Microscope: A GIDAS-Based Analysis of the Prevalent Crash Scenario,“ in *Proceedings of the 27th ESV Conference*, NHTSA, 2023.
- [8] GIDAS (German In-Depth Accident Data), *PCM Pre-Crash Matrix*, Data Years 2005-2022.
- [9] Euro NCAP, *Assessment Protocol – Vulnerable Road User Protection, Implementation 2023*, 2022.
- [10] Euro NCAP Project SECUR , *Deliverables D1.1 and D1.2*, 2022.
- [11] H. Feifel und M. Wagner, „Harmonized Scenarios for the Evaluation of Active Safety Systems based on In-Depth-Accident Data,“ in *Proceedings of the 8th International Expert Symposium on Accident Research (ESAR)*, 2018.
- [12] Euro NCAP, *Assessment Protocol - Safety Assist Collision Avoidance, Implementation 2023*, 2022.
- [13] B. Erdem, H. Feifel, M. Menzel und R. Gee, „Reducing Traffic Fatalities using Collective Perception in V2X Communication based on Crash Data in Japan/Germany/US,“ in *Proceedings of the 27th ITS World Congress*, 2021.
- [14] BAST (German Federal Highway Authority), „Requirements to Driver Assistance Systems from the Road Safety Perspective,“ 2007.
- [15] Euro NCAP Project SECUR, *Deliverable D3.1*, 2022.
- [16] PARTS (Partnership for Analytics Research in Traffic Safety), „Real-World Effectiveness of Model Year 2015-2022 Advances Driver Assistance Systems,“ 2022.
- [17] Canalis, *Huge opportunity as only 10% of the 1 billion cars in use have ADAS features*, 2021.
- [18] L. Cornec, T. Unger, R. Rössler, H. Feifel, T. Hermitte, Y. Page, N. Puller und M. Mousavi, „Analysis of the European Car Road Crashes for the Identification of the Main Use Cases for a Significant Road Safety Improvement through V2X,“ in *Proceedings of the 27th ESV Conference*, NHTSA, 2023.
- [19] European H2020 Research Project PROSPECT, *Deliverable D2.3*, 2018.
- [20] European H2020 Research Project SAFE-UP, *Deliverable D3.4*, 2022.