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How AI and V2X are modernizing our intersections

According to the World Bank, 56% of the world's population live in cities and the trend is expected to continue, with urban populations doubling in size by 2050.[1] In cities across the United States, traffic congestion is a daily struggle for many, and the importance of efficient traffic management and the safety of our roads is paramount.

While there are many contributing factors to overall road safety, intersections are one area that influence overall safety, both positively and negatively. Intersections are high-traffic areas, but also major points of potential accidents and bottlenecks given the potential number of vehicles and pedestrians present at the same time.[2]

According to data from the National Highway Traffic Safety Administration (NHTSA), 10,626 traffic fatalities occurred at roadway intersections in the United States in 2020, including 1,674 pedestrian and 355 bicyclist fatalities.[3] These intersection fatalities represent 27% of the total 38,824 road traffic deaths recorded in 2020. Intersections serve as crucial junctions where multiple streams of traffic converge. Their proper functioning directly affects the overall flow of vehicles and pedestrians, helping ensure a smooth transportation system. Inefficiencies at intersections can lead to congestion, delays, and increased accident risks. Therefore, optimizing these areas should be a key priority for transportation authorities around the world.

With the advent of artificial intelligence (AI) and vehicle-to-everything (V2X) communication, tools are available to help our intersections become smarter, safer, and more efficient. In this article, we will primarily focus on intersection safety, exploring possible safety solution capabilities and how the synergy of AI and V2X technology can help improve the safety and functioning of our intersections.

Safety challenges at intersections

The US Department of Transportation's (DOT) has set forth an overarching vision for achieving zero fatalities and severe injuries within the US transportation system.[4] The objective of the National Roadway Safety Strategy (NRSS) is to achieve safer people, roads, vehicles, speeds, and post-crash care. A solution is needed, with US traffic deaths reaching a 16-year high in 2021 with 42,915 people dying as a result of motor vehicle traffic crashes, a 10.5% increase from 2020.[5] Vulnerable road user fatalities (i.e., pedestrians and pedalcyclists) are on the rise with pedestrian fatalities up 13% and pedalcyclist fatalities up 5% in 2021 compared to 2020.

To properly explore improvements to intersection safety, we should understand the root causes and contributing factors that lead to intersection accidents. This involves both the intersection infrastructure itself and other contributing non-infrastructure-related factors. Let's look at few examples below.

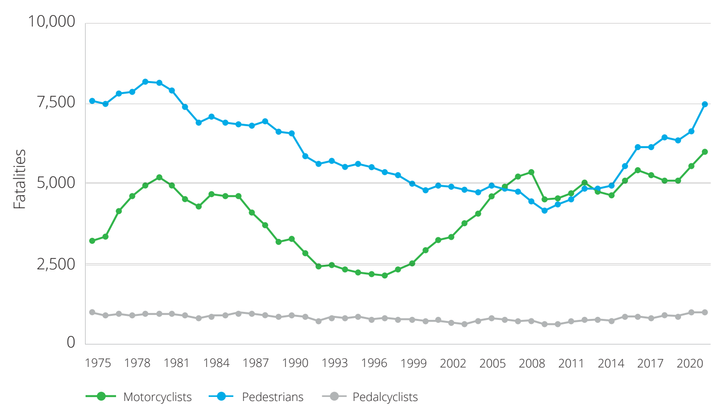
- **Distracted drivers:** Distracted drivers, absorbed in their devices or diverted attention, present a dangerous risk at intersections, leading to preventable collisions. Their lack of focus amplifies the susceptibility of this crucial road point, heightening both the frequency and severity of accidents.
- **Misjudgment of other road users:** Intersections necessitate a heightened state of vigilance, as drivers should assess the timing and intentions of other vehicles, pedestrians, and cyclists. Nonetheless, misjudgments frequently happen due to human error, resulting in accidents at intersections. Additional factors contributing to collisions include obscured objects and unexpected occurrences, such as stoplight violations.
- **Poor visibility:** Environmental factors can hamper visibility at intersections, exacerbating the risks for drivers. Factors such as heavy rain, fog, sun glare, or poorly designed roadway configurations can make it difficult for drivers to see traffic signals or approaching vehicles.
- **Lack of infrastructure optimization:** Intersection design and infrastructure plays a significant role in helping ensure safe traffic flow. However, aging infrastructure, improper lane markings, and outdated signal systems can contribute to confusion and accidents.

Intersection safety system

There are breadth of contributing factors for what makes intersections unsafe, so it could be naïve to expect any solution or system of solutions would prevent all known contributing factors or even prevent all accidents in the future. For purposes of this article, potential solutions should be expected to anticipate, prevent, and mitigate possible unsafe intersection conditions, including impending collisions among and between vehicles and vulnerable road users. Additionally, the solutions should contribute to addressing the above challenges that contribute to accidents and fatalities at intersections, and they should also be forward-thinking solutions. For instance, while autonomous vehicles are still being used only in specific consumer-related settings, current industry trends show that we can expect larger numbers of them on the roads in the future. [7]

One element of an intersection safety system (ISS) is an all-encompassing, AI-driven, 24/7, all-weather 360-degree perception system, powered by an array of sensors including cameras, radio detection and ranging (radars), and light detection and ranging (lidars). Additionally, the safety system should have the capability to forecast path trajectories for every road user, evaluate collision risk probabilities among various road users at the intersection, and promptly transmit warning alerts to those road users via an advanced V2X stack. V2X employs advanced wireless communication technologies, such as cellular V2X (C-V2X), enabling infrastructure-to-vehicle connectivity. This technology enables the exchange of important information, including traffic conditions, road hazards, and warning alerts from an ISS, fostering a dynamic and responsive ecosystem for enhanced road safety and traffic management.

Figure 1: Motorcyclist, pedestrian, and pedalcyclist traffic fatalities, 1975–2021[6]



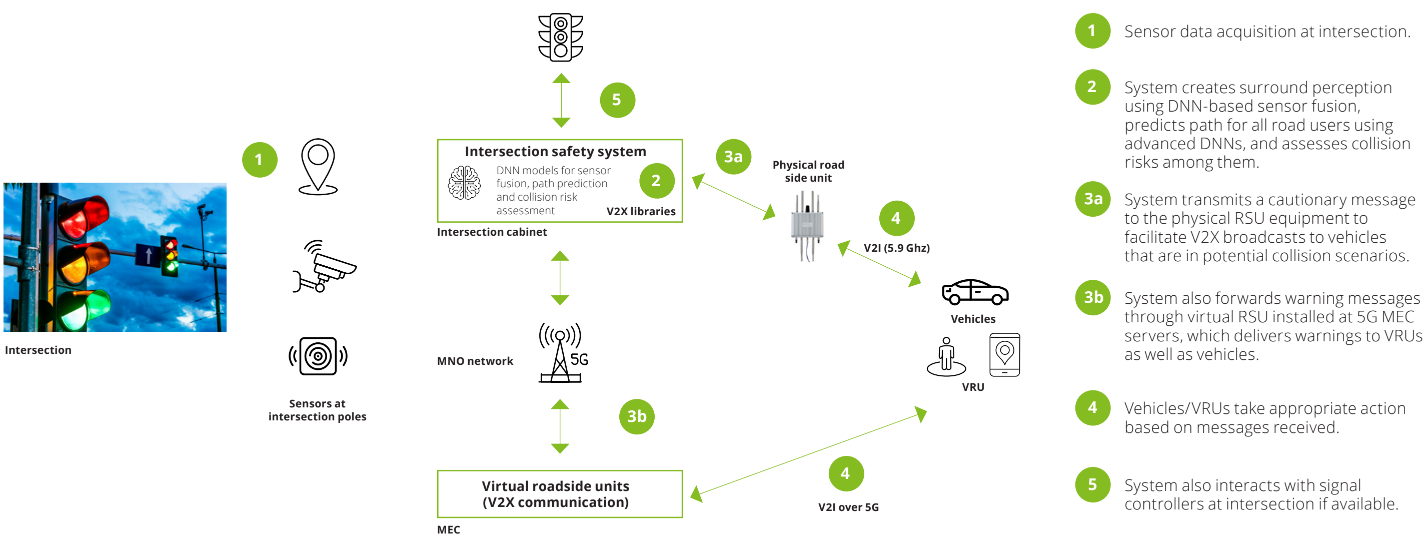
Source: FARS 1975–2020 Final File, 2021 ARF

Generic view of safety system

The system outlined in figure 2 leverages sensor technology, such as camera/radar, (1) multi-modal sensing, to provide all-weather perception capabilities that can effectively mitigate the risks associated with poor visibility and potential fatalities. Furthermore, its AI-powered surround perception system, (2) multi-modal sensor fusion, path prediction, and collision risk assessment, helps ensure the elimination of human driver-related judgment errors. In addition to these advantages, the system proactively issues warning notifications to vehicles, effectively addressing distracted driver incidents, (3a/3b) V2X communication. By providing high-definition maps to vehicles and facilitating signal controller adjustments (5), it also offers a solution for aging infrastructure and the rectification of improper lane markings. An intersection map will be made available to vehicles via V2X communication by physical/virtual roadside units (infrastructure).

Multiple components are at work within this safety system. Next, we'll explore each component and describe key considerations when building ISS components.

Figure 2: Generic overview of intersection safety system



DNN = deep neural network; MEC = Multi-access edge computing; MNO = mobile network operator; RSU = roadside unit; V2I = vehicle-to-infrastructure; VRU = vulnerable road user

Source: Deloitte analysis

Multi-modal sensing

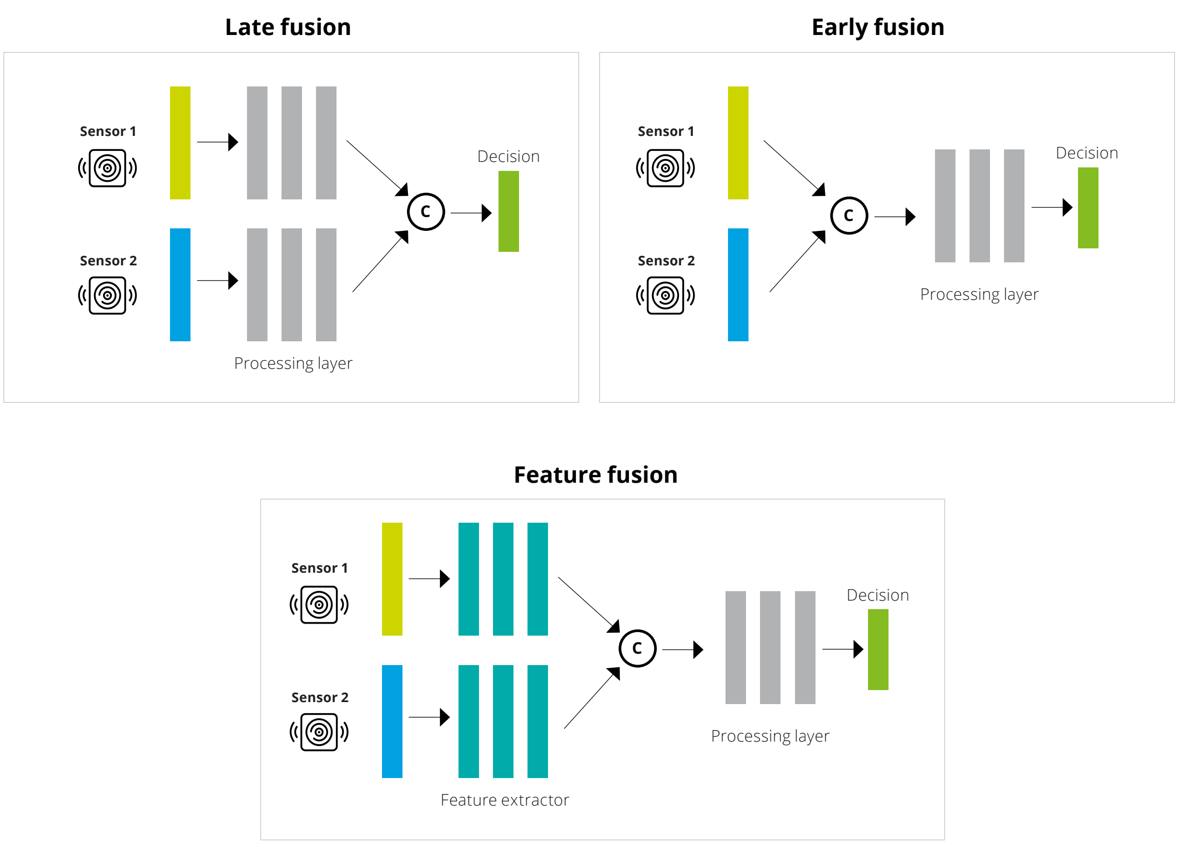
There are various sensors (radars, cameras, lidars, ultrasonics) that can be used for real-time AI perception at intersections. Key performance measures when evaluating the sensors include detection range, resolution, velocity coverage, field of view (FOV), latency, weather resilience, night operation, target classification, color detection, and costs.

By fusing multi-sensor data, the system can harness the complementary strengths of various sensors. The combined sensor data enables robust pedestrian detection, classification, and tracking capabilities, which leverage the accurate distance and velocity information (all-weather support) along with rich visual context. It also enhances the system's ability to precisely localize pedestrians, assess their trajectory, and anticipate potential conflicts with vehicles.

Moreover, this approach also offers redundancy, increasing system reliability and resilience. If one sensor encounters issues related to environmental conditions, the other sensor can provide supplementary information, mitigating the weaknesses of individual sensors and enhancing the overall safety of the pedestrian detection and collision avoidance system.

In practice, the pivotal steps for fusing multi-sensor data include acknowledging common FOV, temporal synchronization among sensors, unified coordinate system (localization), and sensor calibration. Figure 3 shows three commonly used modern sensor fusion schemes: 1) early fusion 2) feature fusion, and 3) late fusion. In the early fusion method, data from various sensors are brought together in their original, raw state. This blending happens right after the sensors collect information. Feature fusion, on the other hand, uses a feature extractor, often a simple neural network, to combine the essential characteristics of the raw sensor data after it's been collected. In late fusion, several classifiers, typically a deep neural network, are employed before combining the data. This method is closely related to making decisions based on the data.

Figure 3: Sensor fusion approaches[8]



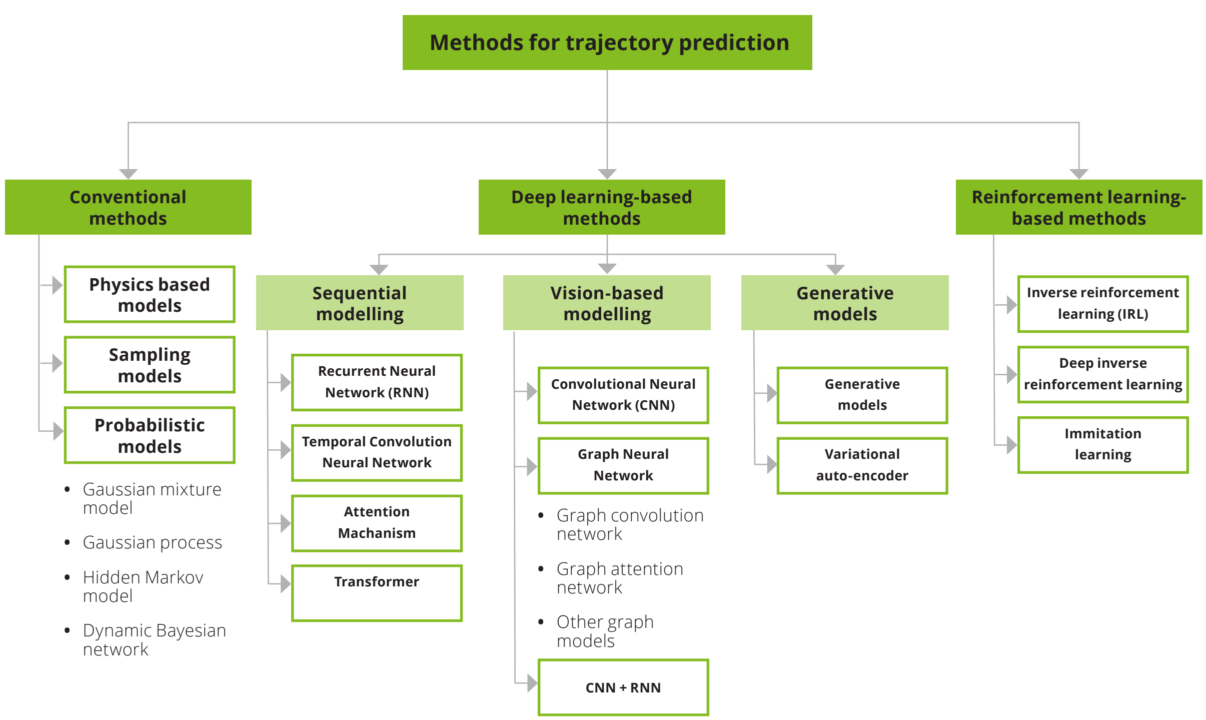
Path prediction

Path prediction for intersection safety is another important component of the intersection safety system. This component anticipates the trajectories of vehicles and vulnerable road users (VRUs). Path prediction involves forecasting the trajectories that vehicles and pedestrians are likely to follow as they approach and navigate through an intersection. By anticipating their respective movements with sufficient accuracy, collisions could be prevented, and intelligent traffic management enabled.

Path prediction is easier for other types of vehicles, like motorcycles, which generally move with car traffic (except when mid-lane) and where riders signal their intended maneuvers. Also, for cyclists, path prediction is possible based on two-wheeler dynamics like motorcycles, but with some more complexity due to higher dynamics (e.g., changing direction or urgent need to navigate around rough road surfaces or obstacles), and cyclists might use the road as well as bike lanes or sidewalks. At the other extreme, path prediction for pedestrians is very difficult because their movements are more random. Pedestrian path prediction will likely rely on knowledge of pedestrians' behaviors, learned over a period of time, and the ability to detect high-risk situations. An example high-risk pedestrian situation might be an individual who is texting on their smartphone while stepping onto the road or into traffic, listening to loud music on a headset, or running to catch a bus. A high-risk place could be somewhere that pedestrians frequently step into traffic.

Various methods have been developed to tackle this complex problem. The approaches to predicting the paths of agents (vehicles and pedestrians) in dynamic intersection scenarios can be categorized into several key categories as shown in figure 4.

Figure 4: Path prediction methods[9]



Collision risk assessment

To reduce the likelihood of false warnings, there should be a set of minimum triggering criteria when determining which road users are at risk of collision. These criteria should consider factors such as vehicle speed, predicted VRU speed and direction, VRU type (e.g., pedestrian, child, cyclist, wheelchair), anticipated VRU position in the future, collision probability, post-encroachment time, time to collision, and external variables such as prevailing weather conditions to score visibility impact, object classifications (truck, van, high-speed vehicle, cyclist, bike), work zones, vehicle size, impact angles, and time of day.

Additionally, safety solutions should assess collision potential for road users, irrespective of the assumption that they will adhere to intersection controls.

V2X communication

V2X technology establishes communication channels between vehicles, vulnerable road users, and infrastructure elements such as roadside units, traffic management systems, and signal controllers at intersections. This interconnected communication system helps to enhance safety and deliver timely warning messages and alerts to road users.

Vehicle-to-infrastructure (V2I) communication can provide a valuable means to enhance road safety. For instance, when the collision risk assessment detects a potential hazard at an intersection, such as a vehicle running a red light, the information is relayed to nearby vehicles equipped with V2X technology. These vehicles can then generate warnings or alerts to their drivers, potentially preventing accidents. Similarly, when vulnerable road users are present, such as pedestrians or cyclists, the infrastructure can send signals to nearby vehicles, to help ensure that drivers are alerted to the presence of these individuals, even if they are not in the driver's line of sight.

An intersection safety system should support both physical roadside units and virtual roadside units to allow delivery to all kind of vehicles and VRUs, allowing broad coverage of all potential road users at intersections.

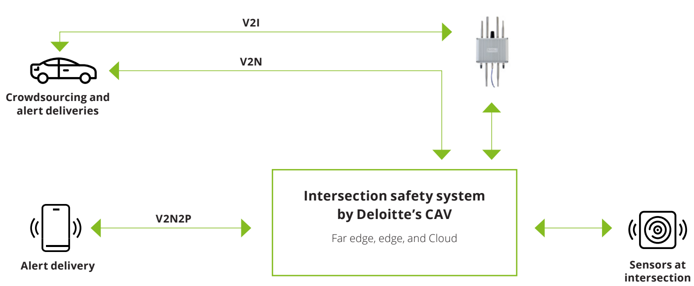
V2X technology can not only facilitate vehicle-to-vehicle communication but also enable V2I communication, allowing for a safer and more connected road environment by swiftly disseminating critical information and alerts to all road users.

Future vehicle-infrastructure cooperative perception

Currently, extensive collaborations between industries and universities are driving the development of V2X cooperative perception applications for autonomous vehicles.[10] This innovative endeavor aims to harness sensors (lidars, cameras, and radar systems) data from intersection infrastructure, effectively integrating it with data from connected and autonomous vehicles (CAVs). This symbiotic partnership facilitates cooperative perception, enabled by V2X communication, where vehicles and infrastructure share sensor information in real time.

As we peer into the future, the horizon holds immense promise. While only time will tell the true results, our aspiration should be nothing less than achieving zero fatalities on our roads. However, as a society, we could be doing ourselves a disservice if we aren't taking advantage of available technologies to do what we can to attain our goal. The transformational potential of vehicle-infrastructure cooperative perception and smart intersections offers a modern, AI-driven traffic management system, which is a great step toward enhancing transportation safety, efficiency, and sustainability.

Figure 5: V2X communications used by ISS



ISS uses various V2X communication paths, including vehicle-to-infrastructure (V2I), vehicle-to-network (V2N), and vehicle-to-network-to-pedestrian (V2N2P).

Source: Deloitte analysis

Endnotes

1. World Bank, "Urban Development Overview," last updated April 3, 2023.
2. US Department of Transportation (DoT), "NHTSA releases 2020 traffic crash data," March 2, 2022.
3. Ibid.
4. DOT, "Implementing the National Roadway Safety Strategy," accessed February 5, 2024.
5. NHTSA, "Newly released estimates show traffic fatalities reached a 16-year high in 2021," press release, May 17, 2022.
6. T. Stewart, *Overview of motor vehicle traffic crashes in 2021* (Report No. DOT HS 813 435), NHTSA, April 2023.
7. Harald Proff, Thomas Pottebaum, and Philipp Wolf, *Autonomous driving: Moonshot project with quantum leap from hardware to software & AI focus*, Deloitte, 2023.
8. Carlos Daniel de Sousa Bezerra, Flávio Henrique Teles Vieira, and Daniel Porto Queiroz Carneiro, "Autonomous robot navigation approach using Deep Q-Network late fusion and people detection-based collision avoidance," *Applied Sciences* 13, no. 22 (2023).
9. Vibha Bharilya and Neetesh Kumar, "Machine learning for autonomous vehicle's trajectory prediction: A comprehensive survey, challenges, and future research directions," *Vehicular Communications*, available online January 29, 2024.
10. Runsheng Xu et al., "V2X-ViT: Vehicle-to-everything cooperative perception with vision transformer," arXiv.org, 2023 [arXiv:2203.10638].