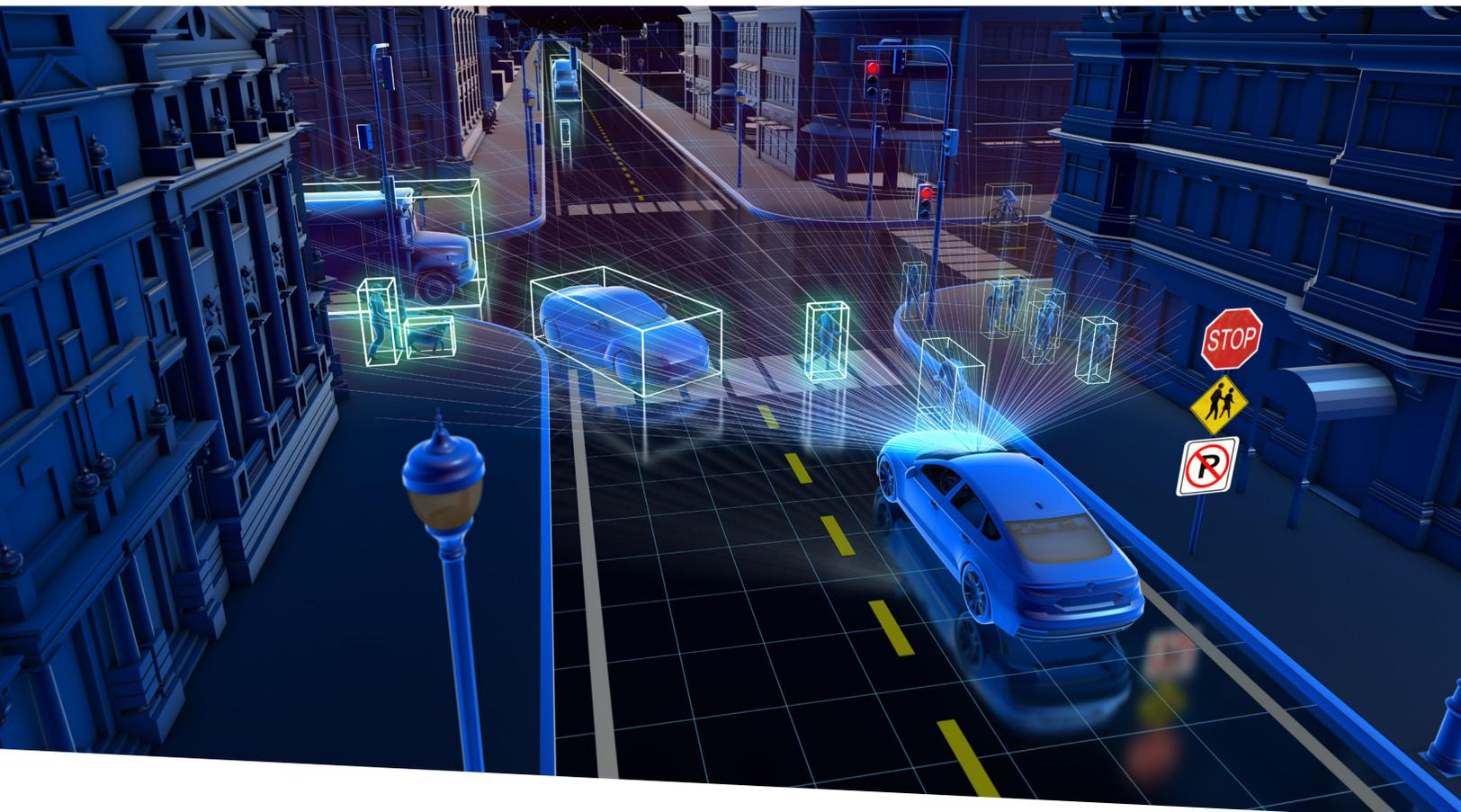


Velodyne Lidar[®]



REVOLUTIONIZING DRIVER ASSISTANCE SYSTEMS WITH FORWARD-LOOKING LIDAR

White Paper

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REVOLUTIONIZING DRIVER ASSISTANCE SYSTEMS WITH FORWARD-LOOKING LIDAR

Most vehicle crashes are forward-facing and result from driver error. Although automakers are striving to develop advanced driver assistance systems (ADAS) to prevent these crashes, there is still significant room for improvement. This paper explores how adding one cost-effective directional lidar sensor would contribute to the prevention of forward-facing crashes.

DEFINING THE PROBLEM

According to our analysis of 2016 figures provided by the National Highway Traffic Safety Administration (NHTSA), at least half of all crashes resulting in death, injury, or property damage were multi-vehicle collisions in which at least one vehicle was forward-facing.¹ All together, this type of crash caused more than 12,000 fatalities; 1,200,000 injuries; and 2,700,000 additional reports of property damage only.² These multi-vehicle crashes include front-to-rear collisions, which comprised 32.6% of all 2016 crashes, and head-on collisions, which represented 2.6% of all crashes. In addition, 20.9% of all crashes were multi-vehicle collisions that occurred at an angle; and it is reasonable to conclude that in the vast majority of angle crashes one vehicle experiences frontal impact.

In the same year, 15.9% of vehicle crashes involved collisions with fixed objects such as poles, curbs, ditches, trees, railings, bridges, etc. These crashes resulted in more than 10,000 fatalities; 370,000 injuries; and 778,000 reports of property damage only. We can infer that the vast majority of crashes with fixed objects that resulted in death or injury were forward-facing.

Additionally, 2.1% of all crashes in 2016 involved pedestrians or pedal cyclists and these incidents were disproportionately fatal, accounting for 16.2% of all fatal crashes, with more than 6,500 fatalities. For both pedestrians and pedal cyclists, most fatalities were the result of impact with the front of passenger vehicles: 87% for pedestrians and 85% for pedal cyclists.³ 75% of pedestrian fatalities occurred in low light conditions.⁴ When we consider collisions with parked vehicles and animals, which combined to comprise 10% of all crashes in 2016, we would expect the same trend to apply--namely, that most harmful crashes involve front impact. Therefore, even if we recognize that some of these collisions involved rear or side impacts, we can conclude that forward-facing collisions with pedestrians, cyclists, animals, and parked vehicles accounted for approximately 10% of all crashes in 2016.

1. National Highway Traffic Safety Administration (NHTSA), "Crashes by First Harmful Event, Manner of Collision, and Crash Severity, 2016," <https://cdan.nhtsa.gov/SASStoredProcess/guest>.

2. These statistics are conservative because they reflect reported incidents, which may have involved multiple fatalities or injuries.

3. NHTSA, "Traffic Safety Facts, 2016: Pedestrians," <https://crashstats.nhtsa.dot.gov/Api/Public/Publication/812493>.

NHTSA, "Traffic Safety Facts, 2016: Bicyclists and Other Cyclists," <https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812507>.

4. NHTSA, "Traffic Safety Facts, 2016: Pedestrians," <https://crashstats.nhtsa.dot.gov/Api/Public/Publication/812493>.

Combining the figures from above (including crashes involving animals, pedal cyclists, pedestrians, fixed objects, and other vehicles both moving and parked) we can conservatively estimate that forward-facing crashes cumulatively represented around 76% of the 7,277,000 total crashes in 2016.

OUTLINING THE OPPORTUNITY AND VALUE OF IMPROVED PERFORMANCE

There are a multitude of approaches for measuring the total impact of traffic crashes and weighing the benefits of different strategies for reducing the harm that they cause. NHTSA calculated that the total economic and societal impact of traffic crashes in 2010 was \$836 billion.⁵ This staggering figure has actually increased in intervening years; between 2010 and 2016, traffic fatalities grew by 12% and injuries by 29%.⁶ Therefore, utilizing the figure we derived in the previous section, a conservative approximation of the total cost of forward-facing crashes in 2016 is \$635 billion (76% of \$836 billion). These forward-facing crashes caused at least 27,000 deaths and 1.5 million injuries.⁷

It is important to note that existing front impact prevention systems are producing significant benefits in preventing forward-facing crashes. For example, the Insurance Institute for Highway Safety (IIHS) reports that General Motors vehicles equipped with AEB and forward collision warning are involved in 43% fewer police-reported front-to-rear crashes than the same vehicles that do not have these features.⁸ This is certainly wonderful; however, it also shows that there remains significant room for improvement. This statistic suggests that even if every vehicle on the road included this advanced driving system, 57% of 2016's forward-facing crashes would still have occurred. Because real world ADAS performance metrics are rarely published, if we apply GM's AEB success rate to other forward facing crash scenarios, unaddressed crashes would have resulted in approximately \$362 billion in total societal harm (57% of \$635 billion).

These conditions present a tremendous opportunity for companies to improve safety. This paper proposes that an ADAS system designed around one forward-facing lidar sensor could prevent 90% of the crashes not currently addressed by ADAS technologies. Such an improvement would prevent \$325 billion in total societal harm (90% of \$362 billion). Achieving this benefit by equipping each of the 288 million vehicles registered in the US in 2016 with a high-performance directional lidar would represent a starting value of approximately \$1,100 per unit. As will be outlined below, a system designed with one lidar sensor as an essential perception component would greatly enhance the safety performance of advanced driving systems.

5. NHTSA, "The Economic and Societal Impact of Motor Vehicle Crashes, 2010"; <https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812013>.

6. NHTSA, "Traffic Safety Facts 2016," <https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812554>.

7. NHTSA, "Crashes by First Harmful Event, Manner of Collision, and Crash Severity, 2016," <https://cdan.nhtsa.gov/SASStoredProcess/guest>.

8. Insurance Institute for Highway Safety, "GM Front Crash Prevention Systems Cut Police-Reported Crashes," <https://www.iihs.org/iihs/news/desktopnews/gm-front-crash-prevention-systems-cut-police-reported-crashes>.

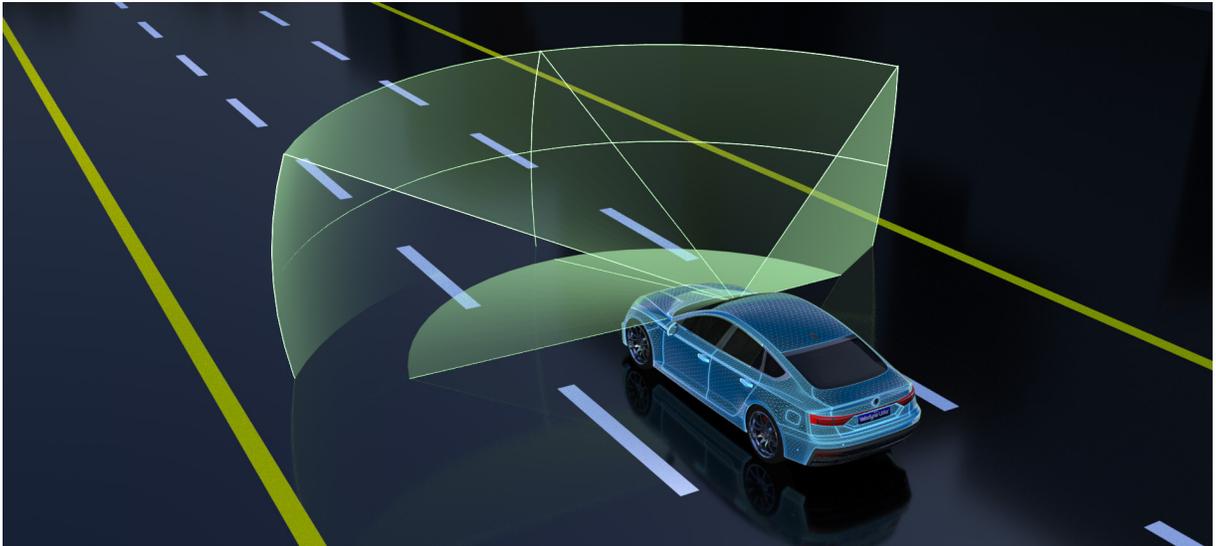


Illustration of Velarray's horizontal and vertical field of view.

CURRENT ADAS STRATEGIES AND HOW LIDAR HELPS

Automakers have invested heavily in developing advanced driver assistance technologies to make driving more comfortable and safe. The most advanced of these systems are already offered as vehicle features that satisfy Level 2 automated driving as defined by the Society of Automotive Engineers (SAE) and incorporate capabilities such as Lane Keep Assist (LKA), Adaptive Cruise Control (ACC), and Automatic Emergency Braking (AEB). Although these features can intervene in certain driving scenarios to control the vehicle's movement, to ensure safe operation the driver must remain attentive and focused on the driving environment.

To date, these L2 systems have been designed around camera and radar technology. However, automakers can greatly improve the effectiveness and efficiency of driver assist features by employing a system in which lidar is a key perception component. Lidar technology is inherently superior to camera and radar in certain performance aspects that are crucial for avoiding forward collisions and which support a move within the industry to implementing lidar as a key sensor for ADAS applications.⁹

Lidar performs free space detection more efficiently and precisely than cameras by providing real-time measurements of how far surrounding objects are from the vehicle, with no additional computational processes or sensors required. As a result, data from a single lidar sensor directly provides the fundamental building block of a successful driver assistance system: accurate free space detection. That is, lidar utilizes precise distance measurements of surrounding objects to map areas where it is safe for the vehicle to drive.

Radar has the ability to detect some surrounding objects, however its relatively "fuzzy" image does not provide accurate free space detection and makes radar dependent on other sensors for

9. Insurance Institute for Highway Safety, "GM Front Crash Prevention Systems Cut Police-Reported Crashes," <https://www.iihs.org/iihs/news/desktopnews/gm-front-crash-prevention-systems-cut-police-reported-crashes>.

object classification tasks. Furthermore, radar struggles to detect stationary objects. “Millimeter wave radar has high range accuracy, and is little influenced by environmental conditions. But its angle resolution is poor, and the millimeter wave radar is prone to false alarm.”¹⁰ These combined weaknesses result in radar not being very helpful in free space detection.

In contrast with lidar, camera-centric approaches require multiple sensors and complex computational processes to infer distance of surrounding objects and thereby determine safe driving paths. For example, in a “stereo vision” approach requiring at least two cameras, “a depth estimation algorithm uses triangulation between the left and right images to determine the depth of objects in the field of view.”¹¹ Alternatively, if a system utilizes only one camera, the vehicle’s computer must compare multiple frames to simulate a stereo image. However, compared to lidar, this “structure from motion” approach also requires additional computational complexity to derive distance estimates.

The complexity and cost of camera-based approaches are compounded by the fact that cameras suffer from what might be called “tunnel vision.” That is, as cameras focus on objects at greater distances they sacrifice field of view. Any photographer who has utilized a camera’s zoom feature will recognize this phenomenon: focusing on a distant object results in less of the scene being captured in the image. As a result, to achieve the constant high-resolution image needed to detect vehicles, objects, and pedestrians at every necessary range (near, mid, and far) advanced driving systems that are designed around cameras require multiple focal lengths and, therefore, multiple cameras.

Over-dependence on cameras for driver assistance suffers from yet other setbacks. Although current systems often analyze camera images to identify detected objects, “algorithms performing feature extraction from images rely heavily on the presence of ‘contrast’ (either color-wise or intensity wise).” This dependency on contrast can make camera-centric systems prone to optical illusions, for example if the side of a tractor trailer blends in with the sky.¹² Camera-based systems can suffer not only from these false negative readings, but also from false positives. A recent IIHS study revealed that these flawed readings can cause these systems to react inappropriately in real road driving scenarios. “In 180 miles,” the report explains, “the car unexpectedly slowed down 12 times, seven of which coincided with tree shadows on the road.”¹³ This poor level of performance caused IIHS to fear that drivers would actually turn off their vehicles’ safety systems altogether.

Exacerbating each of these characteristic challenges in camera-centric approaches is their relatively weak performance in low light conditions. Cameras, like our eyes, are dependent on ambient light to function. Some companies are exploring engineering work-arounds for this deficiency; for example, by incorporating infrared cameras to improve low light function. Efforts to enhance

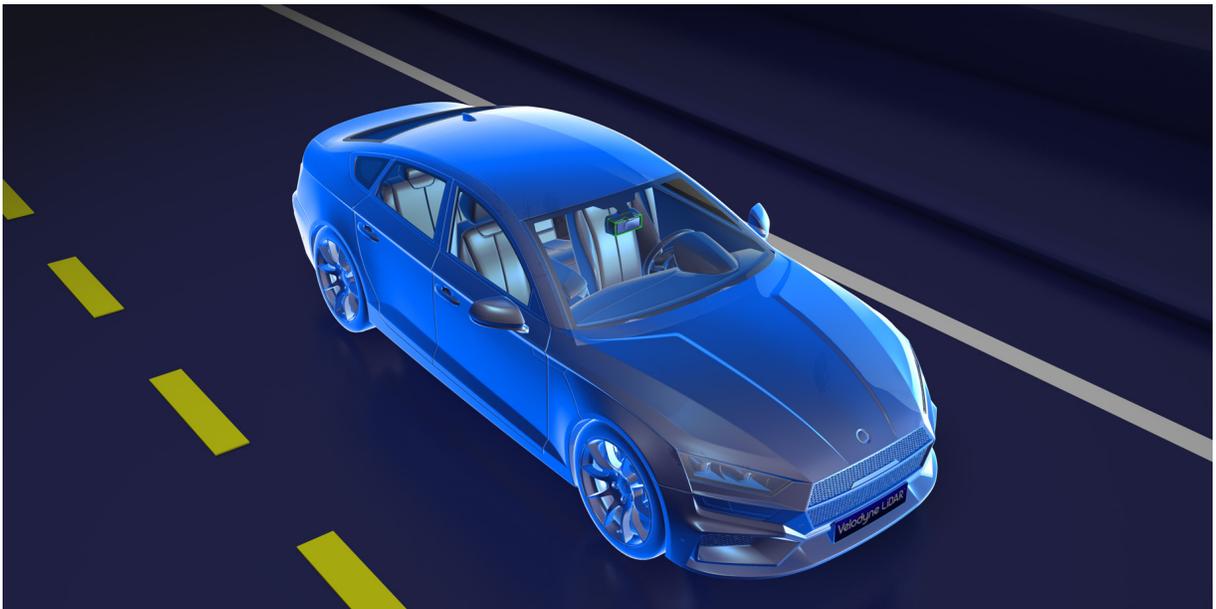
10. Wu, X., Ren, J., Wu, Y., and Shao, J., “Study on Target Tracking Based on Vision and Radar Sensor Fusion,” SAE Technical Paper 2018-01-0613, 2018, <https://doi.org/10.4271/2018-01-0613>.

11. SAE, “J3088: Active Safety System Sensors,” https://www.sae.org/standards/content/j3088_201711/.

12. Iain Thomson, “Man killed in gruesome Tesla autopilot crash was saved by his car’s software weeks earlier,” The Register. June 30, 2016. https://www.theregister.co.uk/2016/06/30/tesla_autopilot_crash_leaves_motorist_dead/.

13. Insurance Institute for Highway Safety, “Evaluating Autonomy: IIHS examines driver assistance features in road, track tests,” Status Report, 53, No. 4. August 7, 2018. <https://www.iihs.org/iihs/news/desktopnews/evaluating-autonomy-iihs-examines-driver-assistance-features-in-road-track-tests>.

existing camera and radar modalities demonstrate not only that automakers recognize that these technologies alone are not capable of solving the problem, but that they are exploring infrared as a possible solution. Therefore, rather than designing patchwork solutions to bolster the performance of any single sensor modality, what is truly needed to cover the gaps in existing approaches is a new sensor technology that provides a different kind of data. To achieve safe operation in a broad range of conditions and contexts, the complexity of advanced driving safety requires automakers to combine the relative strengths of every available and appropriate sensor technology on the market.



Velarray shown mounted behind the windshield.

VELARRAY AS THE CORNERSTONE OF AN ADAS SOLUTION

Because lidars provide immediate and accurate free space detection and excellent object detection and localization, a driver assistance system designed with a high performance forward-looking lidar (FLL) sensor would greatly improve vehicle performance and safety. The most effective FLLs must support the widest range of expected road and traffic scenarios. Additionally, they should enable high resolution perception at long range, such that a wide variety of ADAS features (such as LKA, AEB, and ACC) can be simultaneously enabled. To meet these criteria, the FLL would ideally need to have a field of view of at least 100 degrees horizontally and 30 degrees vertically. The sensor would also need to be able to detect 10% reflective objects at distances of 150-200 m, with a resolution of at least 0.20-0.25 degrees in both directions. Velarray, Velodyne's leading directional lidar tailored for automotive and ADAS applications, is a perfect match for these requirements.

Velarray is lightweight and has a small, embeddable form factor that is perfectly suited to a variety of mounting options, including behind the windshield. Through strategic manufacturing partnerships, this sensor is available for automotive-grade mass production. It is the industry's first 200 m (10% reflectivity) directional sensor for ADAS applications and it has a best in-class horizontal and vertical field of view, coupled with outstanding resolution and point density. The advanced, custom-ASIC based Micro Lidar Array (MLA) architecture of the Velarray also allows for customizability of the field of view and the number of vertical lines within each frame. With a range accuracy of up to ± 3 cm, the Velarray enables excellent object detection and free space measurement. The range

performance of the Velarray is critical for safe driving at highway speeds because, at 70 mph, a vehicle can require 100 m to come to a stop.¹⁴ Vehicles utilizing lidars with ranges ≤ 150 m are therefore likely to result in severe operational constraints.

Empowered by Vella, Velodyne's driving assistance software solution, the Velarray stands at the forefront of ADAS sensor technology. Systems incorporating the Velarray and Vella will outperform the current state of the art, allowing for superior navigation in scenarios that are edge cases for current approaches. These include low light conditions, curvy roads, potholes, intersections, on/off ramps, residential areas, and roadways with unclear lane markings. By translating Velarray's exquisite data set into outputs including dynamic object detection, localization, and free space estimation, Vella enables superior performance for Automatic Emergency Braking, Lane Keep Assist, and Adaptive Cruise Control--the foundational use cases of L2+ ADAS systems.

In summary, lidar technology strengthens current approaches to ADAS by providing another set of perception data that provides real-time free space detection in all light conditions. Building vehicle systems with sensor suites that include lidar along with other sensor modalities enables the strengths of one to cover the weaknesses of the others. When even a modest reduction in frontal crashes would result in the avoidance of significant societal harm and cost, the implementation of a forward-facing lidar sensor represents a significant opportunity for automakers to improve roadway safety.

14. Jamie Condliffe, "Low-Quality Lidar Will Keep Self-Driving Cars in the Slow Lane," [technologyreview.com](https://www.technologyreview.com/s/608348/low-quality-lidar-will-keep-self-driving-cars-in-the-slow-lane/), July 27, 2017. <https://www.technologyreview.com/s/608348/low-quality-lidar-will-keep-self-driving-cars-in-the-slow-lane/>

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