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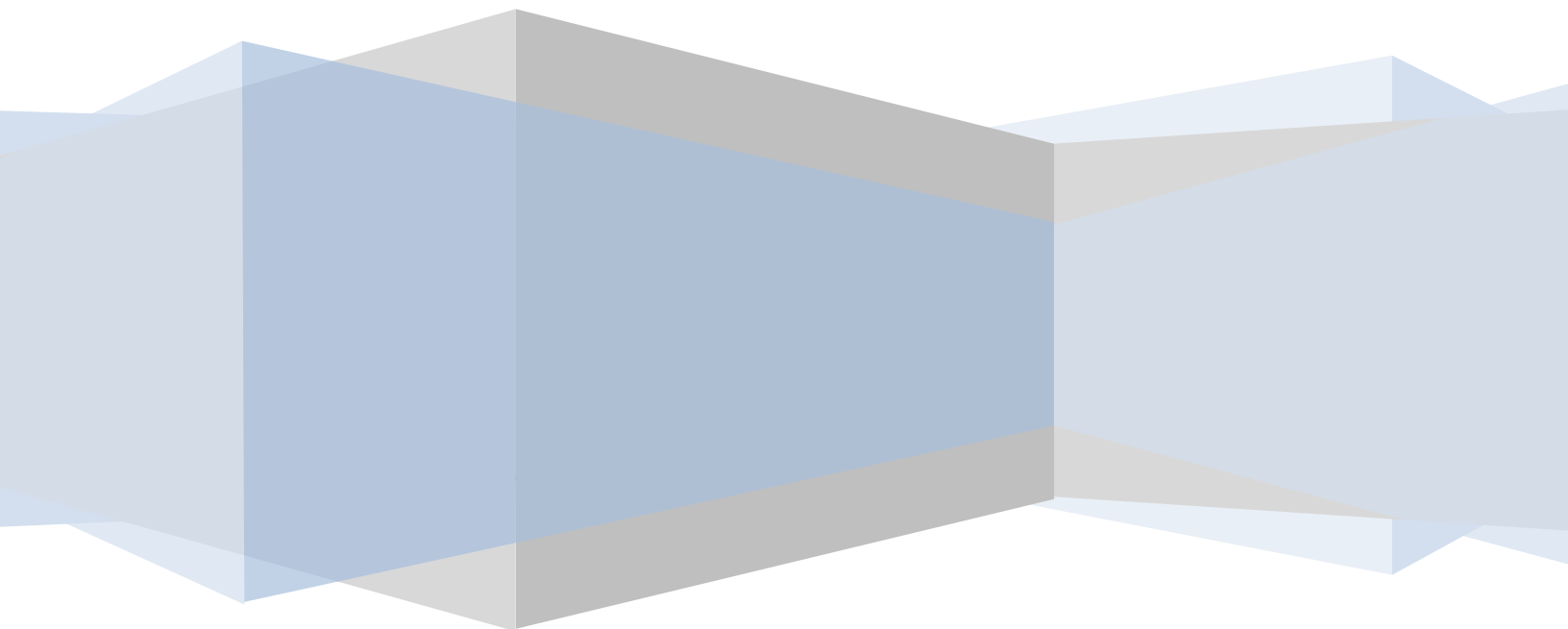
Connected Vehicle Insights

Trends in Roadway Domain Active Sensing

Developments in Radar, LIDAR, and other Sensing Technologies, and Impact on Vehicle Crash Avoidance/Automation and Active Traffic Management

Steven H. Bayless; Adrian Guan; Patrick Son, P.E.; Sean Murphy; Anthony J. Shaw

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Introduction

As the costs of electronic braking, steering, and other control systems fall over time, it is very likely that nearly all new cars on the road will have automotive radar (or some other sensing capability) in the next decades to support some form of automated crash avoidance. The most likely early win will be "forward crash prevention."

Forward Crash Prevention systems are a good place to start. The National Highway Traffic Safety Administration (NHTSA) estimates that there are over 900,000 "rear-end" (or front-to-rear) crashes a year in the US, resulting in over $15 billion in economic losses from death, injury, and property damage. There are relatively few vehicles on the road today with crash prevention systems, but early data and insurance claims are beginning to show that these systems, particularly *Forward Crash Prevention*, are reducing crashes and improving traffic safety.

The objective of advanced automotive research has been to develop new technologies that can prevent an ever wider variety of crash types. The end goal for such research, however, has been to mass produce affordable "smart" cars designed never to crash. The first challenge in developing vehicles that "refuse to crash" is to improve and integrate a growing variety of roadway domain sensing technologies. This paper covers developments in this area, focusing on "active" sensing systems.

The performance and reliability of roadway domain sensing is critical for vehicle applications where maneuvering control may be transferred to, and become the responsibility of, a crash avoidance or driving automation system. Active sensors can measure the location, distance, and speed of potential obstacles on the road more reliably than a driver in most circumstances. However, there are a number of complicating factors. Sensors and systems must potentially distinguish rare, hazardous obstacles from many benign driving situations, a process which requires considering large combinations of both possible conditions. Drivers use training and experience to intuitively model these combinations; they also use context and judgment to assess potential crash threats and to plan and execute driving maneuvers.

It is very difficult, however, to design systems that robustly sense, classify, and assess a large variety of conditions as effectively as conscientious drivers. Although most crash avoidance and driving automation systems still allow the driver to override any automated controls, drivers will expect automated vehicle systems to be more reliable and less error-prone than any other car on the road today.

In particular, the robustness of active roadway domain sensing is absolutely critical to achieving these expectations for reliability. Unlike camera-based solutions, active sensors use their own energy source to "illuminate" potential obstacles. Energy is reflected from a "target" obstacle and measured by the sensor to obtain relative position, speed, and other characteristics. Radar in particular is chosen above a number of similar sensing technologies in intelligent transportation systems because of its relative maturity, reliability, low cost, and robustness in detecting the distance and speed of vehicles under the broadest range of visibility, weather, and other environmental conditions experienced on roadways.

For this reason, radar is the most common active sensor incorporated into vehicle *Advanced Driver Assistance Systems*. Radar is also a key technology in infrastructure-based *Active Traffic Management* – a suite of applications

deployed by road operators to direct traffic and stabilizes vehicle flows in a way that is automated and adaptive to road network conditions. Radar is generally the most robust, cost effective, and non-intrusive sensor for measuring aggregate and lane-level speed and volume in *Active Traffic Management* applications.

Of all the roadway domain active sensing technologies, vehicular radar is the best at detecting typical driving "conflicts" that represent the most common crash risks with others vehicles, particularly front-to-rear collisions. Automotive radars may be mounted in arrays around a vehicle to detect potential angle and sideway impact vehicle collisions as well. Radar does not perform as well in detecting and classifying other common potential hazards such as cyclists, pedestrians, road debris, or roadside barriers. Better crash avoidance systems will likely require improvements in automotive radar sensing, such as improved detection, classification, and threat assessment algorithms for these and other potential hazards. After recognizing that automotive radar is likely to become ubiquitous in new vehicles over the next decade, researchers have focused their efforts on incrementally improving radar's roadway performance.

Even with these improvements, radar will continue to be limited in its capability to detect and classify the entire universe of elements relevant to automated driving beyond braking control. Elements such as lanes and lane markings, road signage and signals, construction equipment and other roadside obstacles, to name a few, need to be monitored if even limited forms of automated driving are to work. More expensive scanning LIDARs (Laser Imaging, Detection, and Ranging), such as those utilized in the Google Self-Driving Car, may enable real-time detection and classification of many of these elements for autonomous vehicles in the future. However, the cost and complexity of the LIDAR hardware, software, and geo-spatial data needed to support semi-or fully-autonomous driving are very high, and are therefore still within the realm of applied robotics research and advanced vehicle prototype development.

One compromise solution has been to fuse less expensive radar with other non-active sensors, such as affordable camera-based computer vision systems, to improve sensing reliability, and to enlarge the scope of detectable features to support very limited driving automation. Relatively low-cost driving automation systems are coming soon. These next-generation *Advanced Driver Assistance Systems* rely upon relatively inexpensive fused multi-radar and camera-based sensor arrays, such as those implemented in *Stop-and-Go Adaptive Cruise Control/Lane Keeping Assist*, which will provide limited case, semi-autonomous driving capabilities. This combined feature set is often marketed as *Traffic Jam Assist* (or under a number of similar brand names such as GM's "Supercruise," and Bosch's "Traffic Jam Assistant,"), but is roughly equal to or slightly greater than NHTSA's 2013 Vehicle Automation Criteria Level 2 "Combined Function" category.

Vehicles that meet or exceed NHTSA's 2013 Vehicle Automation Criteria Level 2 are designed to function only in relatively straightforward, non-threatening driving contexts, such as in low speed, congested conditions. These contexts may also include less congested conditions and roadway configurations in which the requirements for complex maneuvering (e.g. frequent lane changing and merging, intersection turns), or the risk of encounters with elements that are difficult to sense (e.g. hidden or obscured pedestrians, bicyclists etc.) are near zero, such as on large, limited-access freeways.

Since drivers in urban areas spend almost a third of their time in congested traffic, it is likely that *Traffic Jam Assist* could increase consumers' consciousness of, and demand for, such automated features in new cars and trucks. Media coverage of the Google Self-Driving Car has already done much to prime the market pump by highlighting the technology's potential and by feeding the driving public's imagination. The introduction of vehicle-to-vehicle safety communications, based upon Dedicated Short Range Communications (DSRC), may also capture the attention of what perhaps may be a new wave of techno-automotive enthusiasts.

However, vehicle-to-vehicle safety communications would also likely have a profound long-term impact on driving automation. Vehicle-to-vehicle safety communications would significantly reduce the cost, and improve the robustness, of roadway domain sensing by several orders of magnitude, particularly when nearly every vehicle is equipped. By combining roadway sensing with vehicle-to-vehicle communications, higher levels of driving automation – from semi- to fully-autonomous driving – will be easier to achieve. The US Department of Transportation (US DOT), in cooperation with the auto industry and many state and local road operators, has been conducting operations research and deployment planning to support the nationwide rollout of a "vehicle area network" that allows cars to communicate with other vehicles and also to intersections, gantries, and other elements of traffic control infrastructure.

Active sensing systems have been at the core of most infrastructure-based intelligent transportation systems for a number of years. Until "driver assist" technologies and vehicle communications are incorporated into more vehicles, an interim solution is the greater deployment of *Active Traffic Management*. *Active Traffic Management* systems rely heavily upon infrastructure-based radar (and other sensing technologies) to track traffic speed, flow, and density in highway corridors. These inputs are used by *Active Traffic Management* systems to adaptively change speed limits through speed harmonization, which is designed to smooth peak traffic flows and reduce the risk of accidents. Infrastructure radar has also been deployed to track individual vehicle trajectories toward an intersection to adaptively change the traffic signal phase – either to increase or restrict flow in a given direction – thus improving the margin for safety for both mainline and cross traffic.

In the long run, such *Active Traffic Management* systems may steadily deploy and incorporate more infrastructure-based active sensing, but will also leverage DSRC for vehicle safety communications and rely upon advances in vehicle *Advanced Driver Assistance Systems*. The US DOT has been exploring a number of long-term concepts, such as *Dynamic Speed Harmonization* and *Cooperative Adaptive Cruise Control*, through their Research and Innovative Technology Administration - Intelligent Transportation Systems Joint Program Office (RITA - ITSJPO).

Technical Foundations for Radar and Other Active Sensing Technologies

Radar and other active sensors infer the speed, bearing, altitude, and range of a given object by generating a signal and analyzing waves reflected off that object. Most laypeople understand the basic function of radar: a radar transmitter emits radio waves (generally called "radar signals") in predetermined directions. When these waves come into contact with an object, they are normally reflected and scattered in many directions. A receiver will then detect the reflected waves and compute distance to the object by counting the time lapse between the transmission of the signal and the reception of the reflected signal. Radar in particular also analyzes any change in

frequency from returned waves to determine the speed of the detected object, taking advantage of the Doppler Effect. (The Doppler Effect is the change in frequency of a wave for an observer moving relative to its source, commonly heard when a vehicle sounding a siren approaches, passes, and recedes from an observer, changing in pitch as it does so.) By differencing the distance and relative angle of an object at two points, all active sensors can calculate the bearing of the object in question.

Most vehicular radars systems utilize either Frequency Modulation Carrier Wave (FMCW) or Carrier Pulse techniques with detection ranges up to 150 meters and horizontal detection angles up to plus/minus 30 degrees. FMCW is the most common technique used in vehicular radar to interpret the reflected signals. The range of an object can be calculated directly from the time it takes to receive the reflected frequency; velocity can be calculated from the Doppler shift. FMCW is generally less costly and complex than other schemes, such as pulse modulation.

Capturing range and azimuth (angular) information with the radar's field of view requires either a mechanical scanning antenna or, more commonly, a non-mechanical phased-array antenna coupled with digital beam-forming algorithms. Incoming FMCW analog channels are then processed by a single digital stream of azimuth/range/velocity sets, which in turn are processed even further to infer the number of objects within the radar's field of view, as well as their location and speed around the vehicle.

Infrastructure radar has been used for traffic operations and speed enforcement for decades before vehicular radar was first commercialized in the late 1990s. Deployment of highway radars in the "X" band (10.5 GHz) and "K" band (24 GHz) began in the mid-1960s and mid-1970s, respectively, and are still operating widely. Radar in the K band has a 250MHz bandwidth which is five times more than X band; therefore, the K band radar's resolution is higher. Currently, the unlicensed 24GHz band is the preferred band for infrastructure radar. Since infrastructure radar coverage areas do not overlap with each other, and operate at a different frequency than automotive radars, there is little need for interference mitigation techniques.

After radar, the most sophisticated and commercialized long-range vehicle-based ranging sensor is LIDAR. The origins of LIDAR applications are in remote sensing and geomatics, but mobile LIDAR was quickly adopted for robotics research and later for automotive applications. LIDAR is an optical remote sensing technology that measures the properties of scattered light (ultraviolet or near-infrared) to find range and/or other information about a distant target. Like radar, LIDAR determines the distance to an object by measuring or triangulating the time delay between the transmission of a pulse and the detection of the reflected light. Laser's shorter wavelength allows LIDAR to measure range information more accurately than radar. LIDAR uses a high-power laser diode to transmit laser pulses with a wavelength in the eye-safe range of 850 nm to 950 nm, and can produce highly accurate distance measurements with resolutions as high as 10 mm.

There are two broad categories of LIDAR systems for automotive use. The most common and commercially available automotive-grade systems are short field of view sensors mounted in the front of a vehicle. These systems often use an oscillating mirror and/or multiple beams to sweep across an arc of 40 to 80 degrees. The second category consists of more expensive, wider field of view devices that are mounted on the side or top of a vehicle to provide 180 to 360 degrees of coverage. These devices are typically used to conduct surveys of road and

roadside infrastructure, positioning road edges, markers, road signs, utility poles, building signs, and other three-dimensional infrastructure features for the development of navigation-grade digital map databases or survey-grade geographical information systems (GIS)/computer aided design (CAD) files. (Most navigation databases that might be found in personal navigation devices – and sourced from the likes of Tom-Tom, Nokia HERE, or Google Location-Based Services – are increasingly incorporating 3D elements that were partially compiled from mobile LIDAR "point clouds"). Typically, high-definition 360-degree LIDAR systems are deployed, in tandem with radar, in research prototype robotic systems and autonomous vehicles, such as the Google Self-Driving Car.

LIDAR commonly incorporates a scanner with oscillating mirrors so that both the azimuth and elevation can be measured. In this way, the resulting three-dimensional point cloud renders a high-resolution depth map which represents the distance from the transmitter, as well as a high-resolution height map which represents elevation. Algorithms that compare the shape of the two- or three-dimensional point cloud to model representations of common road objects (e.g. pedestrians, vehicles, curbs, etc.) allow LIDAR to support object classification in a manner that is similar to computer-vision based systems, but which also allows the accurate determination of the range and speed of a detected object. High-resolution scanning LIDAR rapidly fires 64 lasers and measures backscattered light to image and range the surrounding environment at a rate of 1.3 million points per second. High-resolution scanning LIDAR has a 360-degree field of view with a 26.8-degree vertical reception angle, providing a very large 3D point cloud.

Short-range ultrasonic detectors are as common as radar in automotive applications. Ultrasonic range detection is an active sensing technology that is common in vehicle applications where low speed, close-quarters maneuvering around parked vehicles and pedestrians is common (e.g. *Intelligent Parking Assist* to automate parallel parking). Ultrasonic range detection works in a similar fashion to LIDAR; namely, by calculating the time delay between the transmission and return of energy waves. Instead of using light, however, ultrasonic detectors generate a shock wave using piezoelectric film that converts a high-frequency electrical pulse into an acoustic one. Ultrasonic sensors have a small form factor, thus they are easy to install; they also have high resolution. However, their working range is highly restricted. Most ultrasonic sensors on vehicles can accurately sense objects no more than 2-4 meters away. The propagation speed of sound is much lower than that of electromagnetic waves; therefore, ultrasound has a slower detection response than radar or LIDAR. Furthermore, ultrasound suffers from distortion from environmental conditions like air turbulence and changes in temperature, air pressure, and humidity. Another problem is that accumulations of mud, dust, or snow on the car can block ultrasonic waves (as well as LIDAR).

All active ranging systems are alike in that they can calculate speed, bearing, altitude, and range independent of any reliance on the natural environment or on other systems operating beyond the sensor suite itself. On the other hand, computer vision technology, as well as some geo-location technologies like satellite or terrestrial navigation (e.g. GPS and other aids-to-navigation), can also be used to infer speed, bearing, altitude, and range under rather exceptional circumstances. In contrast to active sensors, non-active sensors depend on variations of natural or (in the case of satellite navigation) man-made electromagnetic phenomena in the environment for detection.

Computer vision systems with stereoscopic camera sensors are a typical non-active ranging scheme. Stereoscopic computer vision-based systems compute the range by triangulation, calculating differences between matching pixels in multiple images. Computer vision does not transmit signals to surrounding objects, but instead depends on ambient lighting in the environment. Computer vision "ranging" solutions therefore typically only perform well in brightly-lit daytime conditions in unchallenging weather (see "Connected Vehicle Insights: Trends in Computer Vision," ITS America. 2011).

Satellites and similar navigational aids passively collect energy radiated from at least three satellite or terrestrial beacons, all of which transmit from a known point cataloged in the navigation receiver. If vehicles become part of a larger networked system in which they may exchange GPS coordinates, then each might calculate relative speed, bearing, altitude, and range from each other. Networked vehicles would only be able to do this as long as they are able to transmit their coordinates near-instantaneously and simultaneously, and are within the coverage area of GPS or some other navigational aid.

Non-active sensing and ranging systems, such as computer vision or satellite navigation, are very common. They are both limited, however, in their ability to support crash avoidance applications in most driving conditions. Both systems typically require a clear view of the sky without significant shadowing from buildings. For computer vision, abundant direct sunlight is necessary, while satellite navigation requires a line-of-sight view of three (ideally four) satellites. This is in contrast to active sensing technologies such as LIDAR, ultrasonic detectors, and especially radar.

However, this discrepancy in performance between active and non-active sensing systems may change over time. The Connected Vehicle system is an evolving vehicle-to-vehicle/infrastructure communications platform designed to allow for the exchange of GPS coordinates, as well as other safety information (as will be discussed later in the paper). Computer vision systems are improving considerably, with some incorporating infrared imagers for nighttime use. Computer vision in particular is a critical sensor for everything from basic *Advanced Driver Assistance Systems* all the way to the most sophisticated autonomous vehicles prototypes.

Performance Factors for Radar and Other Active Sensors

Radar and other active sensing systems are judged by their range, resolution, accuracy, and field of view. Range is the maximum distance at which an object can be detected from a receiver. Resolution is the ability of a device to distinguish between two objects that are close together. Accuracy is the distance between the measured location or speed of an object and its actual location or speed. Field-of-view is the angular horizontal and vertical coverage. Furthermore, two types of radar are used or being developed for automotive applications: Short Range Radar (SRR) and Long Range Radar (LRR). Although both SRR and LRR differ in range and field of view characteristics, they are both found in various vehicular and infrastructure applications. Highway infrastructure-based radars may generally be more accurate than automotive radars, but may vary widely in terms of range and field-of-view, two characteristics which depend greatly upon the application. There are two types of LIDAR used in automotive systems: fixed direction multi-beam; and high definition, shorter range, 360-degree scanning systems. The four performance criteria – resolution, accuracy, range, and field of view – are usually interdependent. A radar system's resolution generally determines its accuracy, and accuracy is often described as the percentage of the

detection range. More importantly, there is a trade-off between range and field of view. Improved range comes at the cost of a narrowed field of view, and vice versa. The combination of range and field of view is one of the key technical criteria in choosing radar-based vehicular applications.

Automotive radars in particular are classified into two categories based on their range and field of view: Long Range Radar (LRR) and Short Range Radar (SRR). Vehicular Long Range Radar typically provides ranges of over 100 meters, is suited for ranges over 30 meters, and can typically detect objects 200 meters away, with no more than a five degree field of view. LRR's field of view is generally ten to fifteen degrees. Short Range Radar has a wider field of view – usually over 30 degrees – but its range is generally limited to 50 meters. Providing short range, 360-degree sensing around a vehicle requires multiple stand-alone radars on the front, rear, corners, and sides of the vehicle, an arrangement which is complicated and expensive to integrate.

Companies like Fujitsu, ADC, Hitachi, Bosch, Delphi, Denso, and others manufacture vehicular radars. It is worth noting that in terms of their technical specifications, the distinction between Long Range Radar and Short Range Radar is not always made clear by suppliers. Instead, they are very often distinguished as a product offering, and in some cases, medium range radar is used as an intermediate variation. In automotive applications, LRR is typically deployed in longitudinal applications such as *Forward Crash Prevention*, while SRR is deployed in lateral applications such as *Blind Spot Detection/Lane Change Assist*. Vehicular LRR usually operates at a dedicated automotive radar band of 76-77 GHz, whereas vehicular SRR operates at Ultra Wide Band 24 GHz. In addition, the 77-81 GHz band has been allocated for SRR in Europe, and the Federal Communications Commission (FCC) is considering allowing 79 GHz in the US

The FCC allowed unlicensed use of the 76-77 GHz band by vehicular-mounted radars in 1995. But because of human health concerns (the maximum allowable exposure to electromagnetic radiation had not been established), the FCC mandated that vehicle-borne radars could only be active and transmitting while in motion. In 2009, the Toyota Motor Company filed a petition for rulemaking requesting that the 76-77 GHz band be opened up for continuous vehicular radar use; i.e., without a distinction between in-motion and not-in-motion vehicles. Following this, the FCC amended its rules to eliminate the distinction between in-motion and not-in-motion vehicles, and to adopt uniform emission limits for forward, side, and rear-looking vehicular radars. On behalf of the CSA79 consortium, Bosch recently petitioned the FCC to permit the operation of unlicensed, short-range vehicular radar systems (SRR) in the 77-81 GHz band, to promote international harmonization and equipment compatibility across several global automotive markets.

Drivers must keep their eyes on the road, but can always use some assistance in maintaining their awareness and directing their attention to potential emerging hazards. In the last decade, the auto industry and the auto aftermarket have experimented with devices that provide drivers with a second pair of "electronic eyes," enabled by simple vision-based data acquisition and processing technology. In 2000, Iteris introduced lane departure warning in Mercedes Actros trucks, one of the first commercially available, large-scale computer vision applications. (Purchased by Bendix Commercial Vehicle Systems in 2011, this system is now marketed under the name AutoVue.) Since then, a number of computer-based vision products have been made available in vehicles. By contrast, road operators have for a long time used computer vision to monitor and analyze the performance of their highway networks.

Table 1: Summary Comparison of Active and Non-Active Sensing Technologies used in Vehicle Crash Avoidance

Sensor Technology	Range	Field of View Horizontal degrees (vertical degrees)	Measurements	General Objects Detected and/or Classified	General Relative Cost to Procure and/or Maintain*	Example Applications or Operations Supported	General Algorithm Complexity and Computing Resources Required for Applications	General Relative Sensing Availability	Applications or Operations Deployed from 2013
Radar Active 76GHz Long Range Automotive	Long 120-200m	Small 8° -16°	Object Distance, Angle, and Speed	Vehicles	Low	Automotive Forward Crash Prevention/Adaptive Cruise Control	Low	High (Rare Radio Interference, Rare weather)	Yes
Radar Active 24GHz Arterial Infrastructure	Long 250m	Small 7° (65°)	Lane volume, average speed, occupancy, Vehicle type counts, average headway, average gap, speed bin counts, direction counts	Vehicles, Occupied Lanes	Low	Infrastructure Active Traffic Management, Intersection Management/Safety	Low to Medium	High (Rare Radio Interference and weather)	Yes
Radar Active 10 GHz Intersection Infrastructure	Very Long 450m	Small 10° (80°)	Object Distance and Speed	Vehicles, Occupied Lanes	Low	Infrastructure Active Traffic Management, Intersection Management/Safety	Low to Medium	High (Rare Radio Interference and weather)	Yes
Radar Active 24GHz Medium or Short Automotive Range	Medium 40m Short 30m	Large 30-80° (16°)	Object Distance and Angle	Vehicle (possibly pedestrians at shorter distances)	Low	Automotive Low Speed FCW/ACC, Pedestrian and Blind Spot Detection	Low (High for Pedestrians)	High (Rare Radio Interference and weather)	Yes
LIDAR Active Multi-Beam Automotive (16 beam)	Long 120-200m	Medium 16°	Object Distance, Angle, Width, Lateral Position	Vehicles, Pedestrians	Low to Medium	Automotive Forward Crash Prevention/Adaptive Cruise Control (FCW/ACC)	Medium	Medium (Some Weather)	Yes
LIDAR Active Scanning (*180-360°* 64 beam - Infrastructure or Automotive)	Medium and Short 50m-120m	Very Large 360° (30°)	Object Distance, Angle, Width, Lateral Position, Shape	Vehicles, Pedestrians, Some Road Features (Lane, Road Edge, Roadside Obstacles)	Very High	Automotive Automated or "Self Driving" and Infrastructure Asset Mapping and Management	Very High	Medium to Low (Most weather)	No (Limited Prototype fleets only)
Ultrasonic Active (and Non-Active) Detector for Automotive or Infrastructure	Very Short 2-4m	Medium 60°	Object Distance (Angle and Velocity if acoustic phased array)	Vehicles, Pedestrians, Occupied Lanes	Very Low	Active: Automotive Parking Assist, Pedestrian Collision Avoidance Non-Active: Infrastructure Traffic Flow	Low	Medium (Weather)	Yes
Stereoscopic Camera Computer Vision (Non-Active) for Automotive	Short to Medium 50-70m	Large 20-50°	Pixel Scale Values to Infer Object Shape and coarse distance and angle	Vehicles, Pedestrians, Some Road Features (lane markings)	Low to Medium	Automotive Forward Crash Prevention and Pedestrian Detection, Lane-Keeping Assist	High to Very High	Low (Some Weather, frequent changes in daily natural illumination and shadowing)	Yes
Infrared (Non-Active) Automotive and Infrastructure	Short to Medium	Large 20-50°	Pixel Scale Values to Infer Object Shape and coarse distance	Vehicles, Pedestrians	Low to Medium	Automotive Pedestrian Collision Avoidance	High	Medium (Some weather)	Yes
Satellite Navigation (Non-Active) with Vehicle-to-Vehicle / Infrastructure Dedicated Short Range Communications (DSRC - "Connected Vehicle")	Very Long 1000m	Very Large 360°	Relative Position (Distance, Angle, Speed) Vehicle Size or Control System Status incorporated into "Basic Safety Message". Other designated message sets include status of Traffic Control Device.	Vehicles, Traffic Control Infrastructure (Devices, Gantry, Signals, Occupied Lanes) and potentially Pedestrians, assuming all equipped with DSRC	Likely Varies Low to Medium, Depending on Application	Most Active Traffic Management, Intersection Management Tolling/Credentialing. Currently six and potentially more vehicle Crash Avoidance warning applications	Low to Medium	High (Except where no GPS reception)	Yes, some Vehicle-to-Infrastructure. No, Vehicle-to-Vehicle (testing, with potential NHTSA decision in 2013 and beyond)

- All assessments may vary depending on application and complexity of application supported

Since radar uses radio spectrum, there are defined power and frequency constraints which radar systems cannot exceed by regulation. These constraints present another key bottleneck which limits radar's range and resolution, and which complicates interactions with other vehicles. One potential limitation is radio frequency interference. As the number of vehicles using radar increases, the units will inevitably begin to interfere with each other.

Techniques will be implemented in new vehicles to reduce inter-vehicle radar interference. For example, one interference reduction scheme would allow a vehicle to recognize its own radar chirp. As participants in the MOSARIM (More Safety for All by Radar Interference Mitigation) project, Volvo and Bosch have been studying schemes to reduce interference between and among automotive radars. The results of this project suggest that cooperative efforts by the manufacturers of automotive radar can effectively mitigate inter-radar interference.

Along with schemes to distinguish radar chirps from one another, some researchers have examined the possibility of embedding messages in chirps to enable some rudimentary vehicle-to-vehicle cooperative safety applications. Cooperative radar-based applications allow the target vehicle to modify the returned radar signal in order to facilitate detection, classification, and vehicle status, thereby reducing detection errors and adding some rudimentary crash avoidance functionality. This concept, however, is still in the research stage.

Radar in Vehicle-based Safety Applications

Human errors are estimated to be the cause of more than 75 percent of all crashes. Different *Advanced Driver Assistance Systems* (ADAS) applications are meant to address different types of driver error. Error comes in a number of forms: driver inattention or oversight, perception errors like driver misjudgment of distance, and driving operation error in a maneuvering response to a potential challenge (e.g. under-braking or over-steering). Vehicle-based radar and other active sensors provide inputs into ADAS that the system uses to plan and execute "intelligent" crash countermeasures or driving automation routines. Automotive radar in particular is designed primarily to identify and correct perception errors that prevent drivers from properly calculating the relative distance to and speed of other vehicles that are, or may potentially be, in conflict with the driver's vehicle.

All ADAS features are implemented differently by automotive manufacturers, and are often marketed under a variety of brand names. Distinctions include a wide variety of operating condition thresholds and features (e.g. daytime only, below certain speed thresholds, warning-only vs. automated response), as well as different driver interfaces, configurations, and alert modes. Despite these wide variations, vehicular radar is likely the most commonly implemented active sensing technology across most ADAS application features today. It is the main technology used for *Forward Crash Prevention*.

Single-function ADAS applications can be categorized by their orientation relative to the automobile: longitudinal (for forward and rearward) or lateral (to the left or right of the vehicle). Current radar-enabled longitudinal applications include *Forward Collision Warning*, *Forward Crash Prevention,* and forward and rearward *Crash Mitigation and Active Occupant Protection*. Current lateral applications utilizing radar include *Lane Change Assist*, also known as *Blind Spot Detection*, which uses radar to detect cars in adjacent lanes, allowing the driver to safely negotiate lane changes.

Radar is the most common sensor technology in *Forward Crash Prevention* systems because it can support driver-assistance functionality along the entire continuum of collision prevention. This continuum includes alerts classified from informational (moderate warning), to advisory (critical warning) to emergency "assist" (partial automated braking control, shared with driver) to emergency automated control (fully automated braking control).

There are several variations of *Forward Crash Prevention* in *Advanced Driver Assistance Systems*, ranked by sophistication. *Forward Collision Warning* (FCW) is a common application that addresses temporary driver inattention or oversight of driving conditions by notifying a driver to brake or evade the collision via a visual, audio, and/or haptic (e.g. vibration) warning that appears when the time to a potential collision is below a certain threshold. However, *Forward Collision Warning* systems rely on the driver to successfully avoid the collision. FCW does not initiate any automatic control of vehicle functions, and may not mitigate potential driver errors or failures in executing evasive maneuvers.

Systems such as *Forward Collision Warning with Brake Assist* (FCW-BA), *Collision Imminent Braking* (CIB), and *Automated Braking* (FCW-AB) are all designed to address driver misjudgments of distance and poor driving reactions to potential collision threats. *Brake Assist* puts the driver fully in control of braking initiation, but automates the degree of braking thereafter. If a CIB system has determined that the probability of a crash is near 100 percent based on radar input, then it will reduce the impact of a crash by braking automatically without driver intervention. The CIB system may come to this conclusion if a driver has failed to heed a warning, notice a potential collision threat, or respond to a crash threat with enough braking force. Full *Automated Braking* systems, however, are meant to avoid collisions altogether, not just to mitigate the impact of a crash. *Automated Braking* is often implemented only at lower speed thresholds, where there are lower risks of surprise merging and cut-ins from other vehicles. Full *Automated Braking* systems are very effective at low speed collisions, such as in stop-and-go traffic, where the biggest threat is not a fatality or injury *per se*, but minor incidents which result in limited property damage and prolonged congestion.

Not only are automobile manufacturers and safety regulators interested in profiling the benefits of collision avoidance systems, so might be insurance companies. Collision prevention systems reduce property damage considerably, as has been shown in early claims histories of vehicles with *Forward Collision Prevention* systems. According to the Insurance Institute for Highway Safety (IIHS), property damage liability claim frequencies for the 2010 Volvo XC60, which is equipped with the *Forward Collision Prevention – Automatic Braking* "Citysafe" system, have been lower than for equivalent midsize luxury SUVs in the same class. Researchers at the IIHS Highway Loss Data Institute (HLDI) determined that forward-collision prevention systems, featuring automatic braking in particular, had 14 percent fewer claims under property damage liability than when compared to the same models without the features.

Active Sensing in Semi-Autonomous Driving Applications

While vehicle collision prevention systems only function largely in emergencies, other active sensing-based *Advanced Driver Assistance Systems* support steady-state control and limited driving automation. These systems

start with automated longitudinal, or headway control built upon *Forward Collision Prevention*, but may soon combine latitudinal or lane control to provide limited "autopilot" features.

The most prominent and simple system is *Adaptive Cruise Control* (ACC - also marketed as "Active," "Automated," or "Automatic" Cruise Control). ACC uses the same concept as *Forward Collision Warning-Automated Braking* — using the long and short range radars to determine a safe stopping distance to actuate the brakes — to maintain a certain speed without encroaching past that distance. *Adaptive Cruise Control* itself can utilize varying degrees of automation which correspond with the speeds at which the application functions. Conventional ACC is designed for highway speeds, where the vehicle's throttle is controlled for moderate changes in speeds. The purpose of conventional ACC is to ease driver workload in free-flow highway driving, however much driving occurs in congested conditions.

The purpose of *Stop & Go Adaptive Cruise Control* is to ease driver workload and stress in lower-speed, congested conditions. However, *Stop & Go Adaptive Cruise Control* still requires the driver to steer. Some newer ADAS features are beginning to automate steering as well. *Lane Keeping Assist* uses computer vision sensors to detect the lane markings where visible, allowing the system to maintain an appropriate lateral position within a lane. Camera images attempt to detect common road marking features such as road, paint, straight lines, and vanishing points. LIDAR has also been used to detect road boundaries such as curbs and berms to assist in lane keeping. Lanes and curbs can be detected as continuous and smooth, but only when lane markings are clearly visible, unobstructed, and unweathered, which puts a premium on road design and maintenance. Daylight, clear visibility, and unchallenging weather conditions are also typically required for robust lane tracking and lane keeping. Despite these operational caveats, *Lane Keeping Assist* is a compelling ADAS feature that can prevent lane incursions or roadway departure crashes.

Traffic Jam Assist is even more compelling than *Lane Keeping Assist* because is adds another layer of automation. *Traffic Jam Assist* combines the longitudinal control of *Stop & Go Adaptive Cruise Control* and the lateral control of *Lane Keeping Assist* to achieve limited driving automation. The purpose of *Traffic Jam Assist* is to provide driving automation in one limited operational condition: low speed congestion. The value proposition for *Traffic Jam Assist* is to reduce the fatigue and boredom of sitting in traffic for long periods of time, as well as to reduce the risk of low-severity, "fender bender" type collisions.

There are very few vehicles on the road today with *Traffic Jam Assist.* Ford, Volvo, Audi, Mercedes, General Motors (GM), and others have developed ADAS along the lines of *Traffic Jam Assist* and marketed their systems under a number of different names with slight variations of features. For example, GM's "Supercruise" enables a similar complement of semi-autonomous driving features and will likely arrive in the marketplace by mid-decade. The advent of these systems, as well as recent states' efforts to change motor vehicle and traffic codes to accommodate autonomous vehicles like the Google Self-Driving Car, has spurred NHTSA to begin categorizing driving automation features by function.

NHTSA's hope is to provide consistent definitions that auto manufacturers and states can use to clearly define where a new feature or set of features reside within the continuum of driving assistance, crash avoidance, and driving automation technologies. Developments in *Traffic Jam Assist* and *Intelligent Parking Assist* appear to

demonstrate that driving automation will start with simple, low risk maneuvering and driving conditions. Recently, some proof-of-concept vehicles have shown the capability to even *self-valet* park, with no driver behind the wheel (specifically a 2012 Audi A7 with "Piloted Parking" feature).

Traffic Jam Assist and other semi-autonomous driver assistance systems still cannot manage automated lane changes, for example, but such features are not far off and could ultimately extend driving automation. ADAS packages that combine all driving environments and operations – such parking ingress/egress, steady state driving, lane changing, and turning and merging at intersections and on-ramps – have not yet been developed commercially. *Traffic Jam Assist*, "Supercruise," and other semi-autonomous driving systems have yet to incorporate automated driving along a large continuum of driving conditions and maneuvers like the Google Self-Driving Car has done.

However, research vehicles such as the Google Self-Driving Car and its progenitors from the Defense Advanced Research Projects Agency (DARPA) Urban Grand Challenge have epitomized the potential end-state of full driving automation. Although the Google vehicle is only a prototype and is not commercially available, the prospect is high that a number of its driving features will make their way into new model light passenger cars and even commercial vehicles over the next several years.

It is too early to tell how attractive driving automation features will be to the driving public. The consumer's perception of value, and most importantly, willingness to pay, varies considerably and is based on preconceived notions and attitudes regarding the relevance and potential benefits of safety and automation features which have been hard to measure. (In stark contrast, large commercial fleet operators can calculate a precise return on investment from operations logs, and later actuarial studies, based upon experience and data from millions of vehicle fleet miles traveled.) *Traffic Jam Assist* in particular may be one of the most compelling driving automation features to be offered to date. On average, drivers in urban areas can spend more than 30 percent of their time in heavy traffic, so the tangible value of these features for consumers would likely be higher than those for conventional active safety systems.

Despite the attractiveness of *Traffic Jam Assist*, *Forward Collision Prevention* are the likely entry point for most *Advance Driver Assistance Systems* in many new vehicles, in no small part because of the affordability of vehicular radar sensors. Market research reports have shown the huge growing potential of the ADAS market. According to the market research firm ABI Research, the global ADAS market will expand from $10 billion in 2011 to $130 billion in 2016. Some form of *Forward Collision Prevention* could be incorporated into 50 percent of new vehicles produced between 2015 and 2025.

Active Sensing in Highway Infrastructure-based Applications

Although the first commercial radars appeared in vehicles in the 1990s, radar has been used in road operations for at least a decade or more. Where speed enforcement and traffic management systems are implemented, a single road operator might potentially operate hundreds of roadside radar sites. Currently, radar is more commonplace

in roadside infrastructure than in vehicles, and will likely continue to be until *Forward Crash Prevention* becomes more commonly available in new vehicles.

Infrastructure radar-enabled applications are broadly categorized as either informational/supervisory, or adaptive. Informational/supervisory systems simply provide road operators with traffic speed and flow data, enabling a Traffic Management Center to send congestion alerts to drivers through dynamic message signs or through other media channels (e.g. radio, online telematics services, connected Personal Navigation Devices, etc.).

The other category of infrastructure radar-enabled applications is "adaptive," where traffic control devices, such as intersections and ramp meters, may be tuned to reflect rapid changes in traffic flow. Infrastructure radars support two basic types of "adaptive" or *Active Traffic Management* applications. The first type of applications modify intersection traffic signal phase and timing (e.g. red/yellow/green) in real time to maximize traffic flow. In some cases, signal phase and timing is actively managed in order to reduce the risk of a collisions at intersections. The second type of *Active Traffic Management* application, known as *Speed Harmonization*, is used to manage traffic and speed on major freeway corridors in order to reduce collision incidents related to differences in speed between adjacent vehicles. Wide variations in speed lead to a higher probability of collisions which, in turn, substantially increase congestion.

Infrastructure radar is typically placed along a highway in "side-fire" mode, with a beam stretching perpendicularly across multiple lanes of traffic. In side-fire, dual beam radars are used to track traffic speed, flow, and even to classify vehicles coarsely by their length. By concentrating an infrastructure radar beam to eight or nine degrees (or using multiple beams), radars can capture the time lapse of a moving object's presence as well as its speed. These parameters can then be used to determine a vehicle's length, once the angles of vehicle direction and radar beam are known. For intersection-based applications that cover multiples lanes of traffic, some infrastructure radars are mounted on masts or on mast arms at intersections.

Intersection safety applications, though not widely deployed, rely primarily upon infrastructure radar for active sensing. According to the Federal Highway Administration (FHWA), there are over 2,000 fatalities at signalized intersections in the US every year, of which 8 percent are rear-end crashes into a stopped or decelerating vehicle, and 42 percent are cross-over "angle" crashes (e.g. one car violating the red light and striking another vehicle from the side, each traveling perpendicular to the other).

Intersection safety applications can use radar to dynamically calculate intersection "dilemma zones." Dilemma zones are those areas in which a vehicle is 2.5 to 5.0 seconds away from arriving at a stop bar at an intersection. In the dilemma zone, drivers are faced with a critical decision – accelerate and proceed rapidly through an intersection, or brake very aggressively. New radars can dynamically calculate the size of these zones by detecting the speed of incoming vehicles.

If an *Intersection Safety/Dilemma Zone Protection* application detects a vehicle traveling at a high speed in the dilemma zone, the radar sends commands to the traffic controller to hold the red phase longer for opposing traffic. Holding the green/yellow phase longer for dilemma zone vehicles may reduce the incidence of rear-end crashes associated with aggressive, unsafe braking ahead of the intersection stop bar. It may also incidentally reduce cross-

traffic "angle" crashes at intersections involving fast moving vehicles in the dilemma zone that run the red light and are struck by opposing vehicles. Preliminary experience from some road operators shows that red light running was reduced by 58 percent (for heavy vehicles that are slower to decelerate the reduction was 80 percent), and severe crash frequency was also reduced by 58 percent. *Intersection Safety/Dilemma Zone Protection* is known under a number of names and research monikers, the most important of which is *Cooperative Intersection Collision Avoidance System (CICAS) – Traffic Signal Adaptation (TSA) Extending All Red,* or *CICAS-TSA.*

Another safety application in the research and development phase that utilizes a network of active sensors is *Intersection Safety/Stop Sign Assist (SSA),* also known as CICAS-SSA. The FHWA and the University of Minnesota conducted a scan of active highway surveillance systems that could support intersection crash avoidance applications at divided, four-lane, non-signalized expressway intersections in rural areas, which have higher-than-expected crash rates. These often devastating, high-speed side/rear angle crashes typically occur when drivers attempt an unprotected right or left turn from a stop sign on a minor road onto a mainline road, misjudging the velocity of an approaching vehicle traveling perpendicularly on the expressway. A network of radars or other active sensors detect the speed of a vehicle (or vehicles) on the mainline expressway and provide an alert to drivers stopped at the intersection of a minor road using a dynamic message sign or other traffic control device. The traffic control device signals whenever there is there is a wide enough "turn gap" to allow a safe turn onto the expressway.

A variation of *Stop Sign Assist* is *Intersection Safety/Left Turn Assist* (also known as CICAS-LTA). *Left Turn Assist* provides drivers with messages that indicate when it is safe to make unprotected left turns. These messages are based on "turn gap" detection by radar sensors placed at conventional signalized intersections. Thus, *Left Turn Assist* operates in the same way *Stop Sign Assist* does for rural non-signalized intersections.

Besides safety applications at intersections, highway infrastructure radar is utilized to improve traffic flow and reduce incidents along major high-speed freeway corridors. *Speed Harmonization* may be built upon a suite of *Active Traffic Management* techniques which includes *Dynamic Merge Control* (also known as active ramp metering), a method to control traffic flow. Entry and exit from a corridor is managed by ramp metering, which works by calculating the length of the vehicle queue on the on-ramp using infrastructure radar (or loop detectors) to determine the highway speed and occupancy in the region of the on-ramp, which in turn are fed into a ramp metering algorithm. The algorithm, based on probabilistic or "fuzzy" logic, determines a meter rate that allows as few vehicles to join the highway mainline as possible, while preventing the overflow of queued vehicles onto adjacent arterial roads.

An approach that combines *Dynamic Merge Control* with *Speed Harmonization* is intended to orchestrate vehicle entry onto freeways and track exits from ramps while simultaneously regulating driver speeds. Infrastructure radar measures speed and flow, and determines early changes in traffic density from entering/exiting vehicles, rear-end crashes, and other incidents that might create a backward-flowing traffic jam "shock wave." Studies show that it is not higher average speeds on the highway that cause crashes and congestion, but deviations from the average speed. Empirical studies examining the relationship between traffic flow-density, speed, and the highway crash rate show that as flow-density increases, the crash rate initially remains constant until a certain critical threshold combination of speed and density is reached. Once this threshold is exceeded, the crash rate rises rapidly.

Studies also indicate that *Speed Harmonization* can homogenize the speeds of all drivers on a given roadway and reduce crash risks, thus reducing incident-related congestion. *Speed Harmonization* is based on the seemingly contradictory premise that you sometimes may need to move slower to go faster. Lane-specific overhead variable speed limit signs mounted along a major corridor instruct drivers in a given lane to maintain a specific speed in order to reduce the large variations in speed which result in the back-and-forth transitions between relative free flow and stop-and-go conditions.

The rise in rear-end crashes may be caused by increased traffic density without a corresponding reduction in speed. In these conditions, vehicle-to-vehicle headway is so compressed that drivers find it difficult or impossible to compensate for even slight driving inattention or braking error to avoid a crash. Infrastructure radars may be able to measure and detect when these traffic flow-density and speed thresholds are reached, and alert drivers through variable message signs or dynamic speed limits to slow down and maintain a new constant speed.

Such corridor management and lane speed harmonization systems have been deployed in the US, but their success has been limited because drivers are reluctant to remain faithful to lane-specific variable speed limits. When deployed outside the US, however, and when combined with driver education and automated enforcement, *Speed Harmonization* has been more successful. Facilities with *Speed Harmonization* in Europe have seen a reduction of up to 29 percent in crashes which result in personal injury, and a reduction of up to 27 percent in collisions which result in heavy property damage.

Sophisticated, large-scale, corridor-level *Active Traffic Management* applications such as *Intersection Safety* and *Speed Harmonization* are still relatively rare. There are a number of reasons for this. Even though *Speed Harmonization* (and peak-period shoulder lane usage) has been implemented widely in Europe, and to some extent in the United States, there is no unified methodological approach to the selection of implementation parameters (e.g. speed limits, intervention triggers, and intervention duration). This has made it difficult for road operators around the country to justify investing large sums in the deployment of such large, complex systems which operators are not sure will be successful once in operation.

Moreover, significant differences between European and US freeways, such as geometric design, ITS infrastructure, and driver behavior, warrant more careful and systematic analysis. These differences also add to implementation and institutional overhead in deploying these systems. This has made any straight transfer of implementation and operational best practices from one global region to another rather difficult.

Critical Limitations of Radar and Other Active Sensing Technologies

Both infrastructure *Active Traffic Management* systems and vehicle *Advanced Driver Assistance Systems* applications work in the abstract by sensing the environment, assessing traffic conflicts, planning solutions, and executing appropriate measures. Such measures include driver warnings (alerts either in-vehicle or through roadside variable message signage); driver assisted or automated evasive maneuvers and occupant protection countermeasures (for vehicles); or changes in traffic control devices such as signals to control traffic direction,

priority, and/or flow (for road operators). In general, threat sensing and situational assessment present the greatest technical challenges.

In vehicles, *Advanced Driver Assistance Systems* are responsible for integrating sensing data, assessing threats, planning responses, and executing responses based typically upon a single high-level goal (e.g. prevention of front-to-rear collision with another vehicle). Some *Advanced Driver Assistance Systems* may support multiple goals, such as the prevention of multiple types of crashes, or maneuvering, braking, and acceleration automation under vigilant driver supervision (e.g. driver-in-the-control-loop). The current crop of research prototype vehicles, like the Google Self-Driving Car, suggest higher levels of automation and lower levels of driver vigilance or perhaps even zero driver supervision, however supervision may be defined. Planning responses and taking actions, whether related to vehicle crash avoidance and driving assistance or to highway *Active Traffic Management*, are generally divided by levels of automation.

NHTSA's *Preliminary Statement of Policy Concerning Automated Vehicles*, released in June of 2013, provides a framework based on "levels of automation" that includes three variations of driving automation and one level of unmanned autonomous operations. Level 0 is normal driving without the benefit of crash avoidance or driver assistance. Level 1 is *Single Function Automation* that provides drivers with warnings or assistance. Level 1 automation, in which the driver is still responsible for monitoring the road for potential obstacles, likely includes *Electronic Stability Control* and *Forward Collision Warning*. Level 2, *Combined Function Automation*, provides multiple driver "assists" which reduce driving workload but still require driver monitoring, such as in *Adaptive Cruise Control/Traffic Jam Assist*. Level 3 is *Limited Self Driving*, in which the vehicle monitors the road for obstacles and executes maneuvers in nearly all possible driving monitoring and crash avoidance functions, but still may require driver supervision (e.g. advanced *Traffic Jam Assist* and beyond). Level 5 is the same as level 4, but without any driver supervision (e.g. a vehicle in which there is no expectation that the driver will be engaged).

No comprehensive equivalent to NHTSA's driving automation framework exists for highway *Active Traffic Management* systems beyond simple informational/supervisory or adaptive/active categorization. Different adaptive *Active Traffic Management* applications may, however, adjust signals and other traffic control devices on different time scales (e.g. daily, hourly, or per minute) and in reaction to different events or measured activity thresholds. Setting these thresholds can be significant in cost and complexity for any given traffic management system.

With few exceptions, the performance and robustness of "sensing" are the greatest determining factors in the level of automation that may be achieved. Distinguishing hazardous obstacles from benign is the main task for sensors, but sensing failures may result in false positives (benign confused with hazardous) or missed detections (hazardous confused with benign). Failures may also be the result of sensor blindness or environmental conditions in which sensors cannot measure the phenomena the sensor is tasked to perform – known as operating availability.

The integrity of sensing is the ability to reduce errors to a measurable predetermined minimum, or to otherwise catch detection failures or false alarms and minimize their impact. There are no metrics for integrity that fit all components or systems, though some rules of thumb suggest that crash avoidance (but not driving automation)

must perform to the standard of 1 false alarm per 1 million kilometers driven. By comparison, the average mileage between crashes is 800,000 km, and the average annual mileage per driver in the US is 23,000 km per year. The Google Self-Driving Car has succeeded in traveling 500,000 km without a crash.

There are three broad technical limitations of most roadway domain active sensing technologies. The first is the operating availability or robustness of that sensor to changing external environmental and road conditions. The second is sensing "performance," discussed earlier, which describes the kind of measures, or the type of phenomena a sensor can "detect," such as obstacle presence, relative distance, bearing, and speed. Performance may also include object "classification" – object size, shape, and higher level attributes that, when measured together, enable *Advanced Driver Assistance System* or *Active Traffic Management* applications to determine whether a roadway object may be a pedestrian, small vehicle, large vehicle, road marker or sign, an item of debris, or some other categorized object type. Lastly, sensor integrity is the ability to take high-confidence measures with rare missed detections/classifications or false alarms, while any rare errors that do appear are appropriately handled by the automation system or the driver/operator. Taken together, operational availability, performance, and integrity of a given sensor or combined fused group of sensors, define the degree of automation that a vehicle ADAS or highway *Active Traffic Management* system can support.

Environmental operating conditions comprise the first key element of robustness. All-weather operation is a key engineering requirement for nearly any roadway product. Highways are highly dynamic environments which include variations in lighting, barometric pressure, wind, precipitation, and temperature that can fluctuate based on geography and time of day. Though radar's performance degrades to a small degree in rain, snow, and fog, it is able to retain decent acquisition accuracy, which is in stark contrast to the performance of other active technologies such as LIDAR, ultrasonic or non-active computer vision-based imaging sensors. The performance of LIDAR and ultrasonic sensors may be greatly affected by weather, while the performance of computer vision may be reduced considerably not just by weather, but also by natural lighting conditions that may change in the course of a single day. Radar outperforms all of these systems in terms of robustness to environmental conditions.

The last element is sensing performance, or the ability of the sensor to display the most complete picture of the driving situation. One element of sensing performance is the ability to detect obstacle presence, relative distance, angle, range, speed over the largest possible sensing coverage area, and, if permitted, object classification. Object classification uses feature extraction to obtain object size and shape in order to determine higher-level object attributes. For example, the difference between the width of a vehicle and the width of a pedestrian is considerable, so distinguishing object width may allow a classification algorithm to differentiate between the two objects and categorize them properly.

Factors that affect sensor performance include resolution, accuracy, range, and field of view. One of the biggest constraints is often resolution. For example, one assessment of sensor resolution can be made by looking at how ADAS must treat multiple vehicles. Multiple vehicles may need to be tracked, but their paths may not be distinguishable, especially if two or more vehicles cross paths, an occurrence that happens during overlapping lane changes. (Detection of lane changing is of particular interest at multi-lane intersections and on freeways, and is a consideration in determining the type of deployment and placement of infrastructure-based radar.) Successfully

tracking multiple vehicles in close quarters to each other depends on the resolution of the radar or LIDAR, as well as on the algorithms that determine vehicle path history to infer future tracks.

Successful tracking may also depend on differences between the radar cross-sections of different vehicles. Some objects may be hard to distinguish because they present a smaller cross-section as a result of their size or shape; certain objects may absorb radar signals instead of reflecting them. The reflective profiles of roadway targets are typically not uniform, and therefore make obstacle detection difficult and classification sometimes impossible. In this way, the so called "classification" of the object may influence whether it may be detected. For example, materials that are good electrical conductors and which are flat, exposed surfaces, such as metal bumpers, reflect radar signals more strongly. Larger vehicles typically have prominent surfaces of these materials and hence have a larger radar profile, but many objects on or near a highway may have smaller profiles, such as pedestrians, fallen trees or other non-metallic debris.

Since radar can only detect objects with a suitable and well-known reflective profile, it is very limited in detecting potential obstacles smaller than vehicles. The detection range for an object with a smaller reflective profile, such as a pedestrian, may not be great enough to enable a timely collision warning. For instance, a Long Range Radar with a nominal sensing range of 150 meters can detect an animal or pedestrian only within 100 meters. Likewise, a vehicle traveling at 105 km/hour (65 mph) under ideal conditions (zero grade, no ice or water on a newly paved road) would take about 100 meters to stop, assuming a deceleration rate of 0.4 g (4 m/s^2). This distance would be short enough to comfortably avoid a stationary vehicle at 200 meters, but not short enough to stop before colliding with an animal or a pedestrian that is within 100 meters. Furthermore, driver reaction times, system latency, and poor road conditions can substantially increase stopping distances. While it is possible to stop a vehicle noticeably quicker by decelerating at a faster rate, high deceleration rates tend to defeat one of the purposes of an ADAS system, which is to allow the driver to avoid a collision without the dangers associated with heavy braking, like loss of control and/or rear-end collisions from vehicles that are following too closely. Therefore, the characteristics of the radar must be carefully matched to the target profile and performance thresholds of the application.

Improvements in radar detection algorithms and the cataloging of radar cross-sections, however, may reduce missed detection errors in radar sensing. There have been a number of research efforts, such as those from the Toyota Collaborative Safety Research Center and Ohio State University for example, that have sought to improve radar's capability to detect and classify pedestrians. Factors which affect the determination of a radar cross-section include radio wave reflection characteristics such as the average value of the radio wave reflection intensity of an object that is relatively close to the sensor, as well as the range of fluctuation. If radio wave cross-sections of objects are known and can be cataloged, the performance of ADAS using a radar sensor can be refined. The hope is that such research efforts will allow auto manufacturers to adapt radar-based systems to pre-empt crash types beyond vehicle-to-vehicle collisions. These may include crashes with vulnerable road users such as cyclists, motorcyclists, and pedestrians. It is far more difficult to design effective sensing and crash avoidance countermeasures for these types of users – particularly for pedestrians.

As such, LIDAR accuracy and resolution are also relevant to the performance of a number of applications in intelligent transportation systems. Resolution is defined as pulse spacing and pulse density. Pulse density is

calculated as pulses per unit area. For example, coarse resolution (10 points per square meter) is suitable to monitor traffic congestion or parking occupancy, but is not high enough for ADAS and vehicle automation. LIDAR resolution and accuracy for these applications requires point densities of 30 to 100 points per square meter. Such levels of resolution are suitable for freeway and lane-level mapping for vehicle navigation. These levels are also suitable for automated/semi-automated feature extraction and classification of roadside signs and other features, both of which may be helpful for automated lane-keeping in the case of advanced versions of *Traffic Jam Assist*, or *Intersection Safety/Left Turn Assist*.

The last critical limitation is sensor integrity. The integrity of sensing is the ability to reduce sensing errors to a predetermined minimum, and/or to catch sensor failures and to exclude them from being acted upon by a given application. One method to reduce such errors is to improve detection and classification algorithms. However, there is typically a tradeoff between the sensitivity of radar and other sensors and the sensing error rate. The major disadvantage of radar, with regard to other sensing technologies, is its limited ability to classify relatively rare potential roadway obstacles like smaller vehicles, pedestrians, road debris, where the type of obstacle may be critical to the crash avoidance or *Active Traffic Management* application. One option is to lower the threshold for detection, allowing for smaller objects to be detected and ranged in order to reduce missed detections. However, if improved detection algorithms require more sensitive tuning (which in turn may lead to more false positives and therefore more false alarms), then algorithm improvements alone may not produce the level of sensing integrity needed to support critical safety applications.

Many integrity and performance constraints, however, may be overcome with the incorporation of competitive (e.g. redundant) sensing. Competitive sensor fusion, for example, uses two types of sensors to verify the same measure and to thus reduce the probability of a missed detection or false positive. For example, radar (or LIDAR) may detect the presence of an unknown object and may classify it by evaluating the object's radar cross-section (or LIDAR 3D point cloud). However, the cross section cannot be relied upon alone, and verification may be done by evaluating an image of the object using a computer vision/camera-based sensor. *Forward Collision Prevention* applications often compare a radar cross-section with a simultaneous camera image to differentiate, for example, a vehicle from some less relevant road obstacles.

The incorporation of redundant sensing is usually a more expensive proposition and adds complexity, requiring development of sensor fusion algorithms that can correlate measurements from two or more sensors. In many cases, sensor fusion methods, although expensive, can be the only way to enhance the integrity of sensing enough to expand the scope of crash avoidance applications beyond advisory warnings to automation features. Without sensor fusion techniques such as those employed in the most advanced commercially available ADAS features and Self-Driving Vehicle prototypes, fallback to driver judgment and control is necessary.

A self-driving vehicle may need sensing and threat assessment algorithms for a very large combination of basic driving maneuvers (braking, acceleration, turning, lane changes, etc.), highway configurations (intersection, ramp road, multi-lane road), and environmental conditions (weather, visibility, etc.). If not all of these combinations can be sensed or assessed, then maintaining driver vigilance is the only way to compensate for gaps in operating availability, performance, or integrity. Driver vigilance and control is also important when sensing systems have a

reasonable likelihood of a failure that might affect safety. Such scenarios include when systems sensing and automation features are unavailable because a sensor system either goes offline or stops functioning properly.

One of the most difficult problems facing researchers who investigate the commercialization of Self-Driving Vehicles is how to keep the driver engaged to the degree that they may intervene when robust vehicle sensing is unavailable, or when particular threat assessment and maneuver planning cannot cope with an unexpected driving scenario. If the performance and integrity of sensing (and the crash avoidance or driving automation features that rely upon sensing) cannot be reasonably guaranteed, then driver "controllability" is the key.

Developing standards with which to measure and document "controllability" is a new endeavor. The International Standards Organization *ISO 26262 Road Vehicles Functional Safety* standard suggests a method to understand, categorize, and manage functional safety requirements for automotive sensing and automation systems so that these systems are able to cope with a clearly defined and evaluated set of scenarios. Automotive Safety Integrity Levels (ASILs) measure of the risk imposed by a specific system component if it fails.

Roadway sensing may become a major component within this risk inventory.   As risk increases, more stringent methods (such as sensing redundancy) must be employed to ensure safety. The ASIL for each component in a system is determined by three factors: severity, probability, and controllability. "Controllability" is the probability that harm can be avoided when a hazardous condition occurs, either due to actions by the driver, or by external measures. For example, a "driver measure" would be if an ACC "unintentionally" accelerates the vehicle and fails to maintain adequate headway to the vehicle in front of it, the driver intervenes by pressing the brake pedal to override and deactivate the ACC. An "external measure" might be if a vehicle is unable to decelerate fast enough when approaching a signalized intersection, prompting the traffic signal controller to adaptively hold the red phase longer for cross traffic in order to prevent a side impact collision (e.g. *Intersection Safety – Dilemma Zone Protection*). At some stage, driver measures and external measures may become intertwined as vehicle and infrastructure intelligent transportation systems communicate and build upon one another.

The cost and maturity of high-performance sensing are major factors in the affordability of *Advanced Driver Assistance Systems*. The less expensive these systems are, the easier it is for manufacturers to incorporate additional sensors, such as computer vision imaging, ultrasonic sensors, or vehicle-to-vehicle communications, all of which may improve the availability, performance, and integrity and ADAS features. The costs of radar and ultrasonic detectors in particular are likely to decline as production volumes rise over time. LIDAR deserves particular attention because of its high level of performance, its critical role in self-driving vehicles, and its high cost. The LIDAR suite for the Google Self-Driving car can cost up to $70,000. (The cost of all automation modifications made to the Google Self-Driving Car total nearly $150,000, far beyond the average price of a new passenger vehicle, which is estimated to be around $30,000.)

LIDAR vendors like Velodyne, SICK, IBEO, Denso, and Hokuyo, among others, are targeting the automotive systems market. A nascent market for fully automated vehicle systems, such as a potential future commercial version of a Google Self-Driving car, would be critically dependent on reducing the cost of sensing. However, it is uncertain whether or not economies of scale in the global car market might eventually bring down the cost of LIDAR, let alone a complete autonomous vehicle system.

The cost and maintenance of LIDAR may be the one of the most critical bottlenecks to the commercialization of high-level automated "self-driving" vehicle systems. In the interim, radar is mature and relatively inexpensive. Radar cross-section libraries (or when LIDAR becomes more affordable, point cloud profile libraries) for a number of potential targets such as small vehicles, motorcyclists, pedestrians, and road obstacles can be developed along with detection algorithms to improve and expand ADAS and *Active Traffic Management* applications over time.

The Fusion of Active Sensing and Vehicle/Infrastructure Safety Communications

In the future, there will be an ever wider variety of communication and sensing technologies embedded in vehicles, from AM/FM/HD radio, radio-frequency tolling tags, to satellite, Bluetooth, and cellular. Diagram 1 shows the variety of wireless and active sensing systems utilized in highway transportation. A relatively new technology is *Dedicated Short Range Communications* (DSRC). Vehicle-to-X (X is for vehicle, infrastructure, or device) safety communications utilize *Dedicated Short Range Communications* technology to warn drivers of dangerous vehicle conflicts or potentially hazardous roadway conditions.

DSRC is a Wi-Fi-based wireless technology that enables reliable, low-latency communications at highway speeds among vehicles, as well as between vehicles and specialized roadside elements such as tolling gantries, traffic signals, and parking facilities. Cars which have crash avoidance applications which utilize DSRC will be able to securely and privately exchange GPS coordinates and critical safety data with relevant neighboring vehicles, with the goal of reducing the risk of vehicle-vehicle collision. Under the US DOT's Connected Vehicle program, the federal government hopes to kick-start the deployment of DSRC in light-duty vehicles sometime after 2013.

Diagram 1: Vehicle and Infrastructure Communications and Active Sensing Technologies
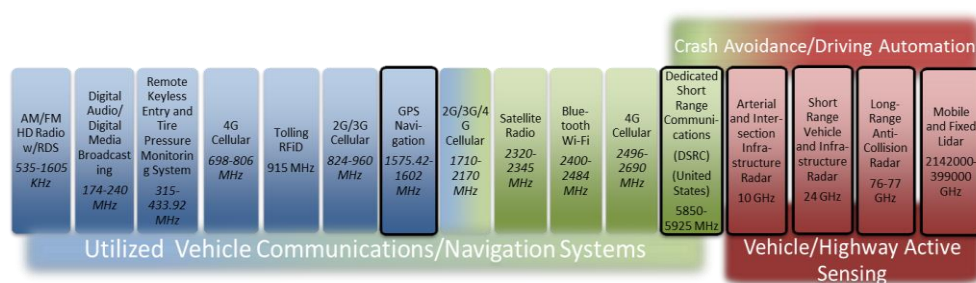
Even though active sensing systems such as radar and LIDAR are ideal for measuring vehicle presence, speed, and traffic flow, such systems cannot receive messages or "warnings" from vehicles, pedestrians, or traffic control devices (e.g. intersection traffic lights, ramp meters, dynamic message signs, etc.). Active sensing systems are also limited in their range and field of view, and must expensively integrate multiple arrayed sensors to achieve full coverage around a vehicle to support 360-degree crash sensing.

Vehicle DSRC provides a 360-degree field of view, compared to about 60 degrees for non-scanning short range radar, and has a range of 1 to 1,000 meters, compared with 250 meters with long range radar. All active sensing systems are line-of-sight, whereas DSRC-based collision avoidance applications can potentially detect range, speed, bearing, and other vehicle attributes which are not directly within the line-of-sight of other active sensors, or which may be masked by other vehicles or roadside objects such as buildings. Like radar, DSRC can operate in nearly all weather and environmental conditions.

Vehicle DSRC supports a number of mobility and safety-critical crash avoidance applications, and the US DOT is currently working with the auto industry to set the stage for the deployment of a core set of such applications over the next several years. Operational testing is now being conducted to evaluate a basic set of vehicle-to-vehicle crash avoidance applications. The core applications include *Blind Spot Warning (BSW)*, *Forward Collision Warning (FCW)*, *Emergency Electronic Brake Lights (EEBL)*, *Do Not Pass Warnings (DNPW)*, *Intersection Movement Assistance (IMA)*, *Lane Change Warning (LCW),* and *Control Loss Warning (CLW)*. Other vehicle-to-vehicle and vehicle-to-infrastructure safety and mobility applications may be built upon the DSRC platform, using a number of messaging sets.

Vehicle-to-vehicle safety applications use the "*Basic Safety Message*" (Society of Automotive Engineers SAE standard J2735), which provides vehicle controls statuses (braking and acceleration), GPS coordinates, and vehicle size, to name only a few data elements. Infrastructure-to-vehicle message sets are numerous, but the primary one is Signal Phase and Timing (SPAT), which provides the signal phase (e.g. Red/Yellow/Green), the time to the next change in phase, as well as a digital lane-level map of the intersection and the configuration of the signal controller. The SPAT message may facilitate and improve vehicle-based crash avoidance applications which execute maneuvers such as acceleration, braking, or turns before an intersection.

A few of these crash avoidance applications overlap with radar-based systems such as *Forward Collision Prevention* and *Lane Change Assist/Blind Spot Detection*. However, many new V2V applications, such as *Control Loss Warning*, allow vehicles to actively warn other vehicles of impending critical maneuvers or inadvertent actions like sudden braking, rollover, or hydroplaning – events that would not necessarily be detected by active or non-active roadway domain sensors. Other applications that facilitate crash avoidance operate far beyond the line-of-sight or range of active sensors. One such example is *Emergency Electronic Brake Lights,* an application which detects braking vehicles several cars ahead in a long queue and warns drivers of hard braking. Similarly, *Do Not Pass Warning* and *Intersection Movement Assist* applications operate at ranges which prevent overtake/head-on collisions on single-lane highways, and high-speed side impact crashes (known as T-bone collisions) common at blind or reduced visibility intersections.

Higher levels of vehicle automation require higher levels of sensing performance and integrity – and the protection from missed detections or false alarms that such increased performance affords – in order to ensure a sufficient level of safety. Vehicle-to-vehicle safety applications are unique in that they rarely suffer from missed detections. Missed detections would occur only in the rare cases of extended radio frequency interference with the DSRC channel, or where there is interference with GPS or extended unavailability of GPS services (e.g. in tunnels or other areas where views of navigation satellites are obscured). False alarms would be rare as well, as GPS coordinates would most likely be verified through GPS augmentations or other GPS receiver-based techniques to reduce positioning errors and improve integrity. Vehicle status information, such as braking or acceleration set points, would also most likely be verified on-board before being transmitted to other vehicles.

As mentioned earlier, the performance of road domain active sensing systems is beholden to a number of unfavorable conditions. Poor weather can reduce LIDAR performance, poor lighting erodes the utility of camera-based sensors, and radio frequency interference can confuse radar. When radar or other sensors fail or are unavailable because of naturally occurring driving conditions, vehicle DSRC can provide the fallback necessary to support a limited level of crash avoidance. Even minimal levels of crash avoidance may be important in reducing the incidence of crashes, injuries, and fatalities over a long period of time.

Furthermore, crash avoidance and driving automation systems of the future will likely evaluate and compare safety messages received from other vehicles through DSRC, with obstacle tracks generated by active sensors to detect potential crash precursors. Fusing active sensing with DSRC-transmitted *Basic Safety Messages* will greatly improve the robustness of *Advanced Driver Assistance Systems* and *Active Traffic Management* systems, allowing for higher levels of automation.

Vehicle Safety Communications and Innovation in *Active Traffic Management*

Infrastructure- and vehicle-based radar systems approach the problem of rear-end crashes from two different perspectives. Vehicular radars used in *Forward Collision Prevention* and *Adaptive Cruise Control* systems are designed to manage vehicle headway and reduce the probability of front-to-rear crashes. *Active Traffic Management - Speed Harmonization* signals drivers to maintain a single optimal speed to reduce the likelihood of collisions and to dissipate congested, stop-and-go traffic flow conditions more rapidly. Combining *Active Traffic Management - Speed Harmonization* and vehicle automation over the long term could meaningfully increase road capacity by reducing the average headway between vehicles, while *increasing* the overall level of safety.

Acceleration time is an important factor to address in *Active Traffic Management*. When cars do not accelerate away from a bottleneck quickly enough, the duration of congestion can increase unnecessarily. It has been observed that cars leaving a traffic jam reach cruise speed much later than predicted by car-following models. This may be because maintaining constant and close headway to the next vehicle during acceleration is particularly uncomfortable (not to mention potentially unsafe) for drivers.

Safely harmonizing acceleration and deceleration patterns in a dynamic fashion may be the next important task for those who design *Active Traffic Management* systems. Drivers' total stopping distance is a combination of three

things: one, the time necessary to perceive a threat and to decide to act (e.g. reaction distance); two, the time necessary to perform the physical movement to activate maneuvers (e.g. brake engagement distance); and three, the device response time (e.g. physical force distance) to slow the vehicle. Nearly half of the stopping distance is created by driver response, and that time varies considerably based on factors such as road conditions, driver engagement, and expectation (i.e. is the driver expecting a potential dangerous situation, or is he or she caught completely by surprise – a case that *Forward Collision Prevention* systems are largely designed to address). The total time needed to accelerate to a given nominal speed is likely similar to braking, in that the time it takes a driver to press the accelerator is the greatest time lag in the process of gaining speed from a full stop.

Vehicle-to-vehicle communications may enable Connected Vehicles to precisely coordinate braking and acceleration, especially from stoplights, within managed lanes, and from on- and off-ramps. With a *Cooperative Adaptive Cruise Control* (CACC) system that utilizes vehicle-to-vehicle/infrastructure communications, a "lead vehicle" could send a DSRC message to following vehicles announcing its acceleration "plan" while at a stop sign or an intersection. (Alternatively, a lead vehicle in a platoon could also send a "deceleration" plan as the platoon approaches an intersection or a highway on-ramp.) Radar or LIDAR could then be used by following vehicles to verify that the lead vehicle is following the acceleration plan precisely. Following vehicles could also use radar or LIDAR to search for and identify any vehicles that might attempt to "cut in" to the lane (for example, vehicles that may not be equipped with DSRC). CACC essentially improves the safety, efficiency, and robustness of such tight vehicle-following, sometimes known as "platooning."

Forms of *Cooperative Adaptive Cruise Control* or "platooning" have been repeatedly tested by researchers. CACC could be built upon radar-based ACC and vehicle DSRC to create platoons of vehicles that are able to travel along a road with braking, vehicle headways (or gaps), and acceleration tightly coordinated among multiple strings of vehicles. In this future concept, V2V-based CACC would be an improvement over conventional ACC, in that both safety and capacity would likely improve by several orders of magnitude at any given speed.

Furthermore, *Cooperative Adaptive Cruise Control* would also allow the coordination of vehicles within a larger *Active Traffic Management* system. It is likely that *Active Traffic Management* applications, such as *Speed Harmonization*, would need to be adapted considerably to allow for central coordination of large platoons of CACC-equipped vehicles. Coupled platoon groups may then be managed from a Traffic Management Center to ensure the safe and efficient formation, passage, and dissolution of platoons through *Active Traffic Management*. Joining a platoon would entail a driver moving into position behind a vehicle (possibly in a specialized, controlled, or "managed" lane) and activating CACC, which would then calculate the distance to and speed of the vehicle while controlling the throttle to maintain a specified range.

A cooperative system "supervisor" would need to determine, through an *Active Traffic Management* system, the recommended platoon entry location and timing for any given vehicle entering a platoon, similar to the way air traffic controllers vector multiple aircraft into an approach toward an airport runway. In this future concept, a lead *Cooperative Adaptive Cruise Control* vehicle, in coordination with a Traffic Management Center, would make the recommendation.

Dynamic Speed Harmonization and *Cooperative Adaptive Cruise Control* are longer-term concepts requiring considerable work to develop requirements and concepts of operation. Nevertheless, they depend on technology upgrades in vehicles which will include DSRC, active sensing, and *Advanced Driver Assistance* applications. The Connected Vehicle system, as envisioned by US DOT, is a platform upon which a number of future advanced crash avoidance and driving automation systems might be built. The Connected Vehicle platform will likely incorporate more elements of vehicle-to-infrastructure *Active Traffic Management* when new technology vehicles, equipped with DSRC, become available in the marketplace.

The US DOT has been exploring a number of long term concepts, such as and *Cooperative Adaptive Cruise Control*, through the Research and Innovative Technology Administration – Intelligent Transportation Systems Joint Program Office (RITA – ITSJPO). The hoped-for widespread commercialization of *Advance Driver Assistance Systems* and Self-Driving Vehicles like the Google Self-Driving Car, along with vehicle-to-vehicle/infrastructure communications, would likely encourage further development of cooperative *Active Traffic Management* systems.

Conclusion

Following the incorporation of electronics in the vast majority of new vehicle control systems, the next hurdles obstructing the advance of crash avoidance systems are the high cost and varying performance profiles of roadway sensing technologies. Combined performance, reliability, and cost issues related to vehicle-based roadway sensing constitute the primary impediments to the development of commercially viable "self-driving" systems. The leap from commercially-available, NHTSA Vehicle Automation Level 1 - *Function Specific Advance Driver Assist Systems* such as *Forward Collision Prevention*, to higher-level "combined function" systems, such as *Traffic Jam Assist*, requires advances in sensing algorithms and techniques that can "fuse" sensor inputs from competitive (redundant) and complementary sensors.

Radar is at the core of forward collision prevention systems for good reason. Radar is the best sensing technology with which to detect typical driving conflicts that represent the most common crash risk: crashes with other vehicles. Radar is alone among all active and non-active sensing technologies in that it can successfully operate in the greatest range of visibility and weather.

All roadway domain active sensing systems can provide high-confidence detection of relative vehicle speeds and trajectories; however, radar is alone among these in terms of maturity and competitive cost. Despite radar's favorable cost/performance ratio, the quality of its sensing capability is circumscribed with regards to physical feature recognition and roadway object classification. Special consideration must be taken to detect obstacle features such as size and width. Consideration must also be taken to track objects smaller than light vehicles at adequate distances, and to identify obstacles such as pedestrians, bicyclists, and road debris that are largely composed of materials that might absorb radar waves. Radar does not detect, or performs poorly in detecting, a number of relevant features that often determine the "intelligent" crash avoidance measure that would be appropriate – e.g. braking, steer-away, or other pre-crash countermeasures. Without improved sensing performance from radar, the number and variety of safety countermeasures that can be incorporated into a vehicle is limited.

Radar's very limited capability to extract features from potential obstacles is being overcome in at least two ways. The first is by making long-term improvements in the radar algorithms which track and classify small or atypical objects that have limited or reduced radar cross-sections. The second is by introducing complementary sensing, often through the utilization of inexpensive "daylight" computer vision-based (camera) sensors. Images of an obstacle are fused with radar tracks to verify a potential crash conflict with a vehicle before a safety countermeasure, such as automated emergency braking, might be initiated.

Finally, three-dimensional "scanning" LIDAR systems, such as the one used in the Google Self-Driving Car, can provide relatively robust all-in-one detection, tracking, and classification for crash avoidance and driving automation. Scanning LIDARs are all-in-one systems in that they can not only determine the relative speed, angle, and distance of obstacles, but unlike radar, they can also classify roadside obstacles and other features, providing a three-dimensional view of the driving environment. Unlike computer vision and radar, the costs of scanning LIDAR systems are very high, and have not achieved widespread commercial scales of application that can push down costs in the near term. However, should prototype automated vehicles (such as the Google Self-Driving Car) enter commercial use, the costs of LIDAR may decline, most likely over an extended period.

To the degree that roadway sensing represents significant cost and performance bottlenecks to advances in crash avoidance and driving automation, reducing the dependence on complex active sensor suites is one option to address this problem. Long-term investment in the deployment of vehicle safety communications for all vehicles would reduce the dependence on expensive sensor suites, and at the same time, would improve the overall robustness of crash avoidance and driving automation systems. With Dedicated Short Range Communications (DSRC), vehicles will be able to exchange safety messages with other vehicles, relying on these messages to confirm obstacle category, range, and speed relative to other surrounding vehicles, doing so securely and anonymously. Vehicle-to-vehicle safety messaging would be used by *Advance Driver Assistance Systems* to catch and correct errors generated by other vehicle-based sensors.

Under the US DOT's Connected Vehicle program, the auto industry and road operators hope to implement vehicle-to-vehicle systems sometime after 2013. Despite these efforts, automotive product developers who seek to integrate ADAS and vehicle-to-vehicle communications into a new vehicle line may succumb to resistance from product development and marketing departments that may be unwilling to price new vehicles out of a particular customer segment's reach. Automotive marketing departments typically seek and predict features that they hope will ignite passion in potential car buyers. Introducing additional costs to pay for extra safety features which are often poorly understood by consumers is often not seen as singular, compelling value proposition that can drive up sales, at least within all vehicle categories.

Feature combinations such as *Traffic Jam Assist* and other *Advance Driver Assistance Systems* beyond NHTSA Vehicle Automation Criteria Level 2 may finally present the type of functionality that may drive market demand for safer, high-technology vehicles. Americans spend 5.5 billion hours in traffic every year, nearly an entire work week per driver. Growing traffic congestion alone may be propelling automakers toward semi-autonomous and autonomous cars. However, there are still some uncertainties, such as whether drivers will really be comfortable

or willing to relinquish control. More experience with automation will be another key element to growing consumer confidence.

But until such advanced systems are found in all vehicles, the incidence of rear-end crashes may be addressed by *Active Traffic Management* systems deployed and managed by road operators. Other adaptive traffic management systems operate at intersections, using radar and other infrastructure sensors to actuate traffic control signals to enhance traffic flow and reduce the risk of intersection collisions. These kinds of highway active management systems are not deployed widely in the US, but may become more widespread if long-term investment in transportation infrastructure increases in the future.

Future *Active Traffic Management* may evolve beyond *Speed Harmonization*, which dynamically "re-posts" speed limits based on traffic conditions. Future *Active Traffic Management – Speed Harmonization* systems may reserve managed lanes for NHTSA Vehicle Automation Criteria Level 3 "Limited Self Driving" vehicles where merging, lane changing, and other traffic mixing is minimized. Such "harmonized" lanes would provide a limited-access, predictable, and structured roadway environment. Such an environment would reduce critical dependence on roadway domain sensing availability, performance, and integrity, thus enabling safe, driver-out-of-the-loop operation.

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